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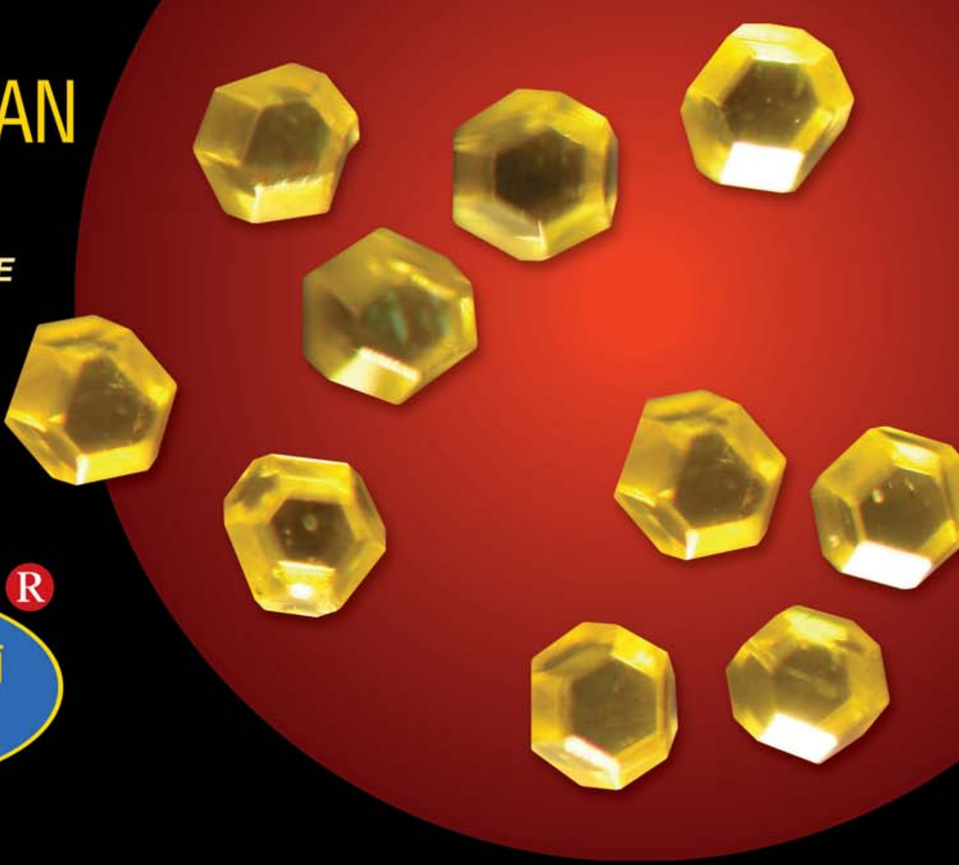

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Photo courtesy of Hughes Christensen showing floor of drill rig and drill bit containing PCD cutters being lowered into well.

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FINER POINTS is the oldest publication devoted exclusively to the understanding, selection and application of diamond, cubic boron nitride and related materials. It is edited for recipients who are involved in some way with these “superabrasives”, either as providers of the materials, producers of products containing the materials or users of these products (e.g., grinding wheels, dressing tools, drill bits, saw blades, sawing wires, cutting tools, polishing compounds, CVD film products, etc.).

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A Finer Point of View…

PRESIDENT
Ion C. Benea, Ph.D.

Year 2009 is quickly coming to an end. What an eventful year it has been for the world at large and for our industry. We have witnessed the superabrasives market coming to an almost stand still in the first two quarters, only to recover modestly in the last two quarters. The superabrasives business, like all other businesses, is still suffering from the worldwide recession and lack of confidence resulted from the economic turmoil of this past year. In retrospect, 2009 was the year when the "great recession" reached its lowest point. It was the year when people gave up trying to predict the year ahead. It was the year when every forecast had to be revised, usually downwards, few times. If we had to pick a date, the recession has probably ended in June. After four successive quarters of contraction, the U.S. economy rose at an annual rate of 2.8 percent in the third quarter. At the end of the summer there was some hope for a rapid economic recovery, but that hope has faded. Much of the slow economic growth we have seen in recent months is attributed to temporary factors: the effect of the inventory cycle as companies restart production following months of stock liquidation and the fiscal stimulus. Analysts had forecast growth to sag a bit in the current quarter and the first half of 2010. They expected consumer spending would weaken under the weight of 10 percent unemployment. Even so, evidence continues to accumulate that global recession is over and that economic recovery has begun, both in U.S. and worldwide. Companies that have remodeled their business to be viable through recession will rebound sooner, stronger, and with a markedly improved strategic position. Nonetheless, we are witnessing a bumpy recovery. Some even fear that it is too soon to know whether the economic recovery will last. To date, the Dow Jones Industrial Average and S&P have gained more than 40 percent, since their March lows. Historically, the market has predicted with remarkable accuracy what is to come in the next 6 to 12 months. If we believe the stock market is one of the best leading economic indicators than we can believe the experts' prediction that 2010 will be a year of economic growth. Yet, as someone once said, "predictions are a dangerous thing, especially those that pertain to the future." The consensus, however, is that 2010 will be a year of modest growth. In November, the U.S. manufacturing sector grew for the fourth straight month, though at a slower pace. A recent Business Roundtable survey indicates that 68 percent of CEOs polled expect the sales of their companies to increase in the next six months. Yet the survey found top executives cautious on making investments in their businesses and even more cautious on hiring workers; only 19 percent of CEOs polled expect employment to increase in the next six months. A major new government stimulus package of additional spending for infrastructure projects and deeper tax breaks for small businesses, amongst other proposals, will be implemented sometime soon. Despite this not so rosy scenario for 2010, we should all be optimistic, if not for anything else, but for the fact that optimists live a happier life. "Tis the season to be jolly!" And, this Holiday Season we have one more reason to be jolly; the so-called "lost year" is nearing its end. We are filled with joy, excitement and hope, in anticipation of the New Year.

Best Wishes for a Healthy, Happy and Prosperous New Year!

Sincerely,

Ion Benea

Ion C. Benea, Ph.D., President
Industrial Diamond Association of America

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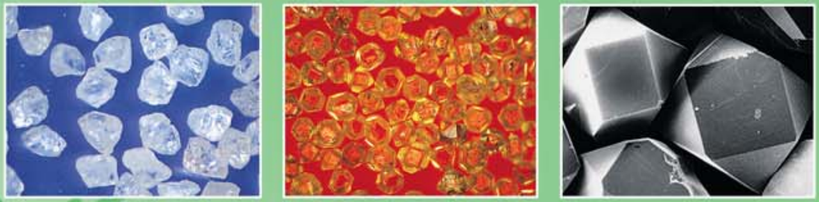

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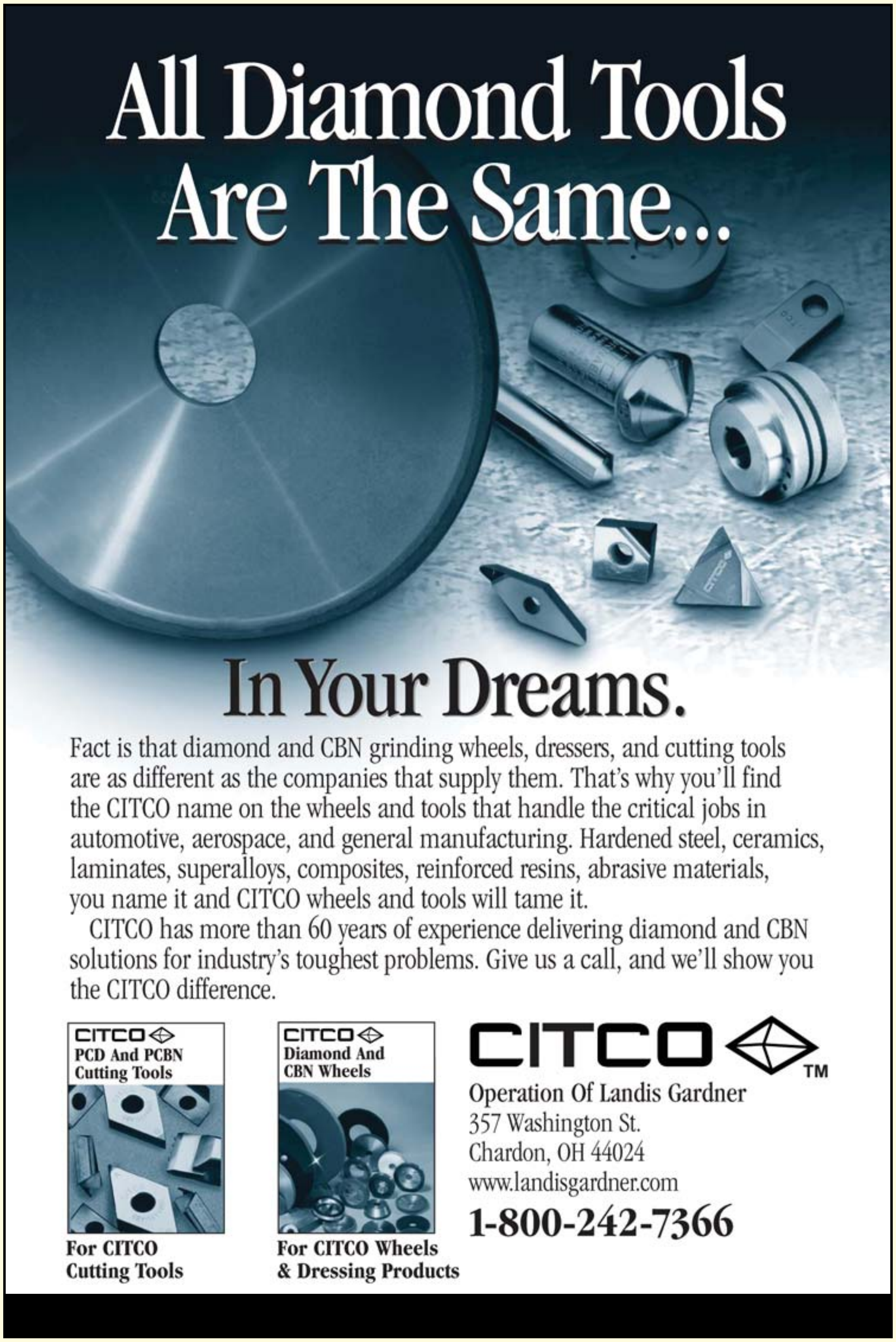
We Will Never Be The Way We Were Before…

This year is closing fast and there is no doubt it was a year that has left companies shaken, business down and individuals struggling to find out where to go or what to do next. At a recent business meeting we were pondering where our industry is heading and how each company will rebound now that we can see the light at the end of the tunnel. Of course everyone wants to be where we were just a few short years ago, but how long will it take to get there and more importantly how do we begin that long journey. One of my colleagues pointed out how they were starting to call people back to crank up production and others chimed in with positive signs from their companies, but the feeling around the room was cautious at best. Then, one person leaned way back in his chair and stared distantly out the window. He spoke softly, but his words hit hard: "We will never be the way we were before and we will never do business the same way. This experience has changed us in a way no one can ever imagine." I thought long and hard about his words, and I found myself longing for the past… Not in a melancholy or sentimental way, but in a way that recalled the energy, drive and dedication I once took for granted. Our industry was as one in thought. We all knew what had to be accomplished. Customer, competitor or supplier all followed the same guidebook for success and drank from the same fountain of knowledge. It was a groundswell of growth and a tidal wave of innovation. That is why we were all successful. Never doing business the same way may be the worst move anyone can make. Yes, we need to be more cautious and more diligent in the details, but we also need to find the right combination that worked before. Yes, the INTERNET and e-commerce are here to stay, but true business relationships were built on a face-to-face relationship and quality products. When someone shook your hand it was a pledge to deliver and be there for you if something went wrong… Tough to get that from an email "out of the office" reply or playing "push the button" only to arrive at a voice mail message. I hope we start to do things the way we did before, because that is how we all achieved the successful business relationships and sales growth in the past. Discount websites and cut throat pricing is not what made us great, having the right product for the right application did! Relationships, customer service and honesty were what kept us getting repeat business. Maybe the problem now is that too many companies have lost that competitive edge and forgotten how to fight the good fight. History tells us where we've been, what went wrong and if we study it correctly it shows us how to reinvent the things that made us great!

Terry Kane, Editor



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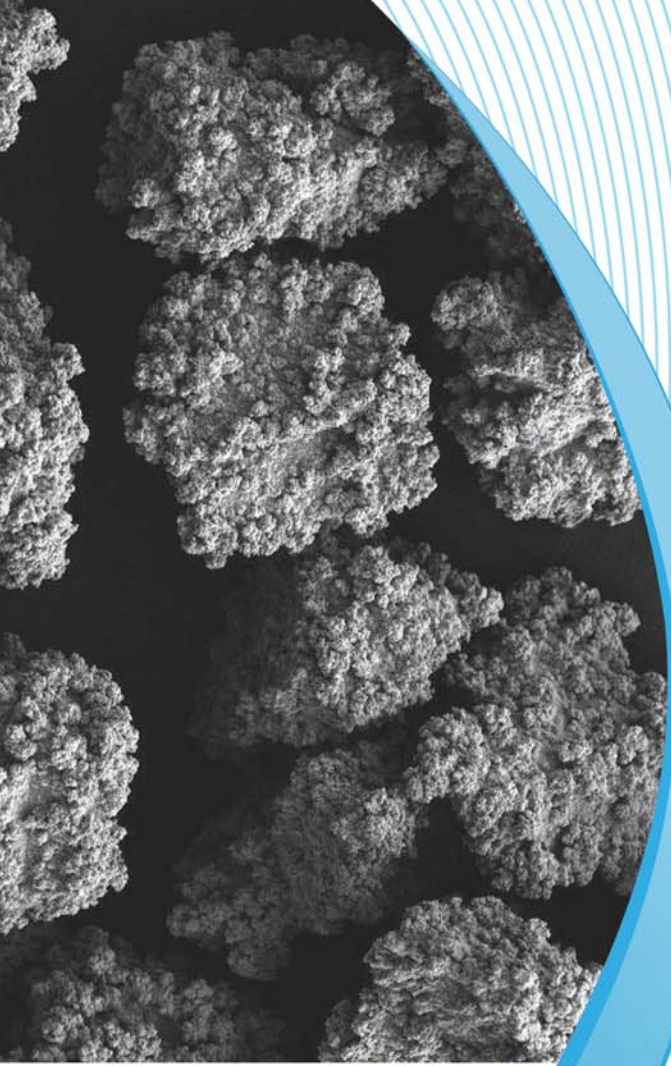
We will never be the way we were before; we will be more creative, more cautious and more deliberate. More importantly we will draw on that same energy that made this industry a place where we all wanted to work.

No, we will never be the way we were before ... ***We will be better!***

All the best in 2010…



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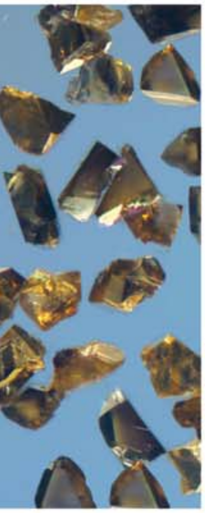

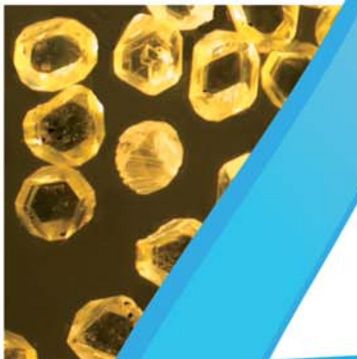

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HOLD THE DATES
May 5, 6 & 7, 2010

Industrial Diamond Association of America

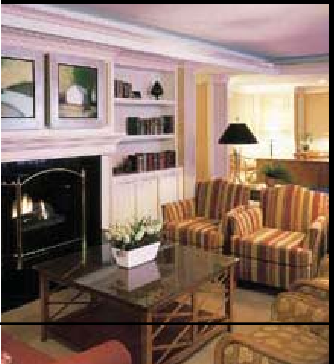
2010 Annual Meeting

Now is the time to make your plans and hold the dates for the 64th Industrial Diamond Association's Annual Meeting. If you have attended the past few meetings you are aware of the quality of our presenters and the value of this networking opportunity. If you have missed being a part of this important meeting, now is the time to let your voice be heard and share in directing your Association. Arrangements are underway and we will have significant speakers to address both the economy and industry issues. Programs are in motion to improve your Association and assist all members in marketing and business development. We have been through a tough year and now all Association Members need to get together and work to continue the early growth we are now seeing! Together we are a powerful force! This year we are meeting at the Hilton Easton www.hiltoncolumbus.com in Columbus Ohio in order to give everyone easy access to the facilities and meetings.

The Hilton Easton hotel is a AAA 4-Diamond, full service, upscale, suburban hotel located in the heart of Easton Town Center at Easton Columbus, Ohio. The hotel is convenient to the Port Columbus International Airport (CMH) and offers complimentary shuttle service to and from the airport. The best shopping, dining and entertainment is literally steps away at the magnificent Easton Town Center. The hotel is only ten minutes from downtown Columbus and 15 minutes from The Ohio State University. The Hilton has recently renovated guest rooms that are warm and inviting and feature all the latest technology, plus:

- Concierge level rooms and private lounge
- High-speed Internet access (for a nominal fee)
- Fitness center with large workout area
- Luxuriously appointed heated indoor pool and whirlpool
- Complimentary Business Center
- Complimentary airport shuttle from 6am to 10:30pm daily

The Hilton offers a full service restaurant and Cappuccino's Coffee Bar for coffee and sweet treats. In the evening, the Lobby Lounge features piano entertainment. Serving ice-cold beer, cocktails and great pub food, the Easton Sports Club is a premier location for catching your favorite sporting events. Plasma TV's with stateof- the-art programming and billiard tables offer even more action! Easton's thriving corporate and retail centers make Hilton Columbus at Easton the perfect location. Just outside the doors of the spectacular Hilton, a world of excitement awaits. Easton Town Center is an uncommon blend: a classic vintage town center, yet a stylish entertainment Mecca. Wander down cobbled walkways to the oldfashioned town square. Discover treasures hidden away in dozens of exotic shops and boutiques. There are more than 100 shops, restaurants, clubs and entertainment sites. It's all just steps from the front door and it's all unforgettable… visit at: www.eastontowncenter.com. The hotel is ten minutes from downtown Columbus and 15 minutes from Ohio State University. Local corporate headquarters for The Limited, JP Chase, Abercrombie & Fitch are close by and Port Columbus International Airport is just four miles away. Complimentary shuttle service operates 7 days a week from 6:00am to 10:30pm.



Hold the dates May 5, 6 & 7, 2010 and watch for more details as plans are finalized!

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NEWS *and* notes

LANDS SUPERABRASIVES ANNOUNCES NEW BROCHURE AND WEBSITE LAUNCH *New York, NY* – LANDS Superabrasives announced that they have published a new full color product line brochure to meet the needs of its global customer base. The brochure details crystal types and application for a wide range of LANDS products with characteristics outlined for the various bond systems available. LANDS Superabrasives, the synthetic diamond division of Lieber & Solow was started in 1981 and today manufactures a complete line of powders, grits and micron powders in its own state-of-the-art facilities. By controlling the manufacturing process, LANDS Superabrasives is able to supply consistent quality products that have gained worldwide recognition. Visit the new LANDS Superabrasive website at: www.landssuperabrasives.com for further information and details.

SCIENCE JOURNALISM AWARDS ANNOUNCED – Apollo Diamond was featured in a television program about growing diamonds in the lab. The program won recognition earlier this month in the 2009 AAAS Kavli Science Journalism Awards. funded in part by the National Science Foundation. "Diamond Factory" was produced by Julia Cort for WGBH's NOVA science NOW, and aired on public television stations in June. It features host Neil deGrasse Tyson showing how materials science offers the means to engineer diamonds with the strength and conductivity of the real thing. Along the way, Tyson variously adopts the persona of Indiana Jones and travels blindfolded to the diamond producers' top-secret location, where he learns that diamonds that can be customized in size and shape offer a valuable resource for future electronics, transportation and communications.

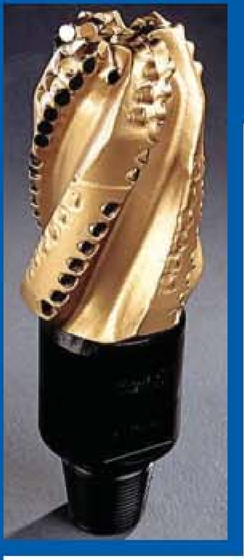
FOUR YEAR LITIGATION RESOLVED *Fort Lauderdale, Florida* – Worldwide Superabrasives, LLC, a leading US based manufacturer of industrial diamond and cubic boron nitride superabrasives, is pleased to announce that the four year litigation with Saint-Gobain Ceramics & Plastics, Inc., has been amicably resolved and the case dismissed on November 10, 2009. The nature of the agreement ending the litigation prevents further discloser of details.

VOLLMER OF AMERICA CORPORATION ANNOUNCES THAT SABER DIAMOND TOOLS HAS JUST ACCEPTED DELIVERY OF THEIR SECOND VOLLMER QXD400 MACHINE – This machine provides state of the art finishing for PCD tools, combining rotary erosion with six programmable axes allowing Saber to continue to provide innovation in tool design. The six-position tool changer allows for flexibility in types of electrodes and polishing wheels that can be utilized in unattended operation.

Drilling Oblique Holes in Duplex Steel with PCD Tools

Dan Scott, Hughes Christensen
John Barry, Element Six

The production of oil and gas in high cost offshore locations requires the use of duplex stainless steel liner pipes in the well bore. Furthermore, efficient production of certain fields require the drilling of secondary bores which in turn requires the penetration of the steel liner in the main bore, so as to enable further drilling through rock. The high cost of operating oil and gas production facilities calls for efficient drilling of the liner so as to minimise the downtime. Limited torque on bit and non-ideal system dynamics limit the degrees of freedom for process optimization. The present work first assesses the suitability of a range of cutting tool materials for cutting duplex steel under a range of cutting conditions. Having thus identified PCD as the most appropriate cutting tool material and having captured and modelled the cutting force data – incorporating the compounded influence of size effect and tool wear – a geometric model is developed which predicts the evolution in the torque and the axial and radial forces acting on the bit.



Considerations For Drilling Steel Linings In Well Bores

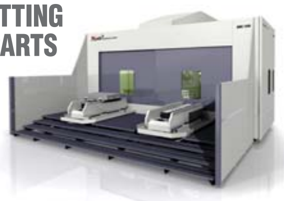
Well bores for the production of oil and gas are frequently lined with metal pipes so as to maintain the integrity of the bore and facilitate servicing. In order to access reserves in different regions of the field, it is sometimes necessary to drill secondary bores off the main bore and in doing so, penetrate the metal liner. Milling an 'exit window' in the liner metal is not straightforward as for the majority of the process, the bit must cut both rock and metal and these two materials impose very different demands on the tool. In the search for greater efficiency, it is further desirable not only to penetrate the well bore lining but also, to continue drilling for a significant distance and ideally, realize the entire secondary bore without having to raise the drill string and replace the bit. Of the metals used for lining well bores, duplex stainless steels are perhaps the most difficult to machine. Even in a metal-cutting shop, where there is free access for manual intervention to the process, duplex stainless steels are notoriously difficult to cut – often requiring very narrow operating windows for even the most moderate tool lives. The combination of a sticky, highly work-hardening stainless steel with an abrasive brittle rock, as in exit window milling, presents a highly demanding bi-material machining process. When compounded with erratic drill string and bit dynamics, the cutting tool materials employed in the bit are subject to extreme abrasive, thermo-chemical and toughness demands. In order to appreciate the workload imposed on the bit during exit window milling, it is useful to consider some of the mechanical quantities involved. With reference to Figure 1, a typical liner pipe may have a diameter, D, of 6 inches (152 mm) or less and a wall thickness of 1/2 inch (12.7 mm). The milling bit typically engages the liner pipe at a slight angle, θ, such that the inclination between the axes of both is just a few degrees. In order to fully penetrate the pipe, the milling bit must progress a total linear distance of several tens of feet and in doing so, remove a volume of liner of several hundred cubic inches, whilst – for the majority of the operation – simultaneously cutting rock. It is clear that the larger the degree of misalignment between the bit and the liner pipe, the lower is the volume of material to remove and potentially, the lower the wear on the cutters, however, the 'angle of attack' is limited in practice by the directional-drilling apparatus. Considering appropriate cemented carbide cutting tool for metal-cutting shops as a reference, a stock removal of 20 cubic inches (0.36 Litres) would be accepted as a reasonable tool life when machining duplex stainless steel. As such, the stock removal in exit window milling can be considered large, even with a bit comprising several tens of cutters and neglecting the wear generated by the rock-cutting element of the process and the dynamic loading due to forced and natural vibrations. It should also be noted that the cutting speed varies across the bit diameter and as such, where an optimum cutting speed might exist, not all cutters can operate under such conditions.

This article outlines a two-part approach to optimizing well bore exit window milling processes. The earlier sections outline a novel laboratory metal-cutting method for testing the wear performance of different tool materials. In the latter sections, a geometrical model is described,

ACKNOWLEDGEMENTS The authors are grateful to Pat Smyth and Neels Pretorious for undertaking the turning tests and contributing to the experimental matrix. Also, the input from Rustom Moody, Bob Bennett, Cal Stowe and the team at Baker Oil Tools is greatly appreciated.

&Announcements PRODUCTS

MAG ANNOUNCES A NEW ANGLE ON HMC SPINDLES FULL TILT PRECISION AND PRODUCTIVITY FOR HEAVY 5-AXIS CUTTING ON LARGE AEROSPACE AND ENERGY PARTS



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Diamond Machining Technology (DMT), a leading manufacturer of diamond sharpening products, today unveiled its Magna-Disc System, an abrasive disc system compatible with Work Sharp machines' Model's WS2000 and WS3000. In the past, these machines had to utilize paper discs to sharpen and hone tools. However, by utilizing DMT's Magna-Discs, sharpening on these machines can be more precise while also saving money on replacement discs. With DMT's Magna-Disc System, there is no longer a danger of excessive heat or sparks, providing a cooler, safer and cleaner working environment.

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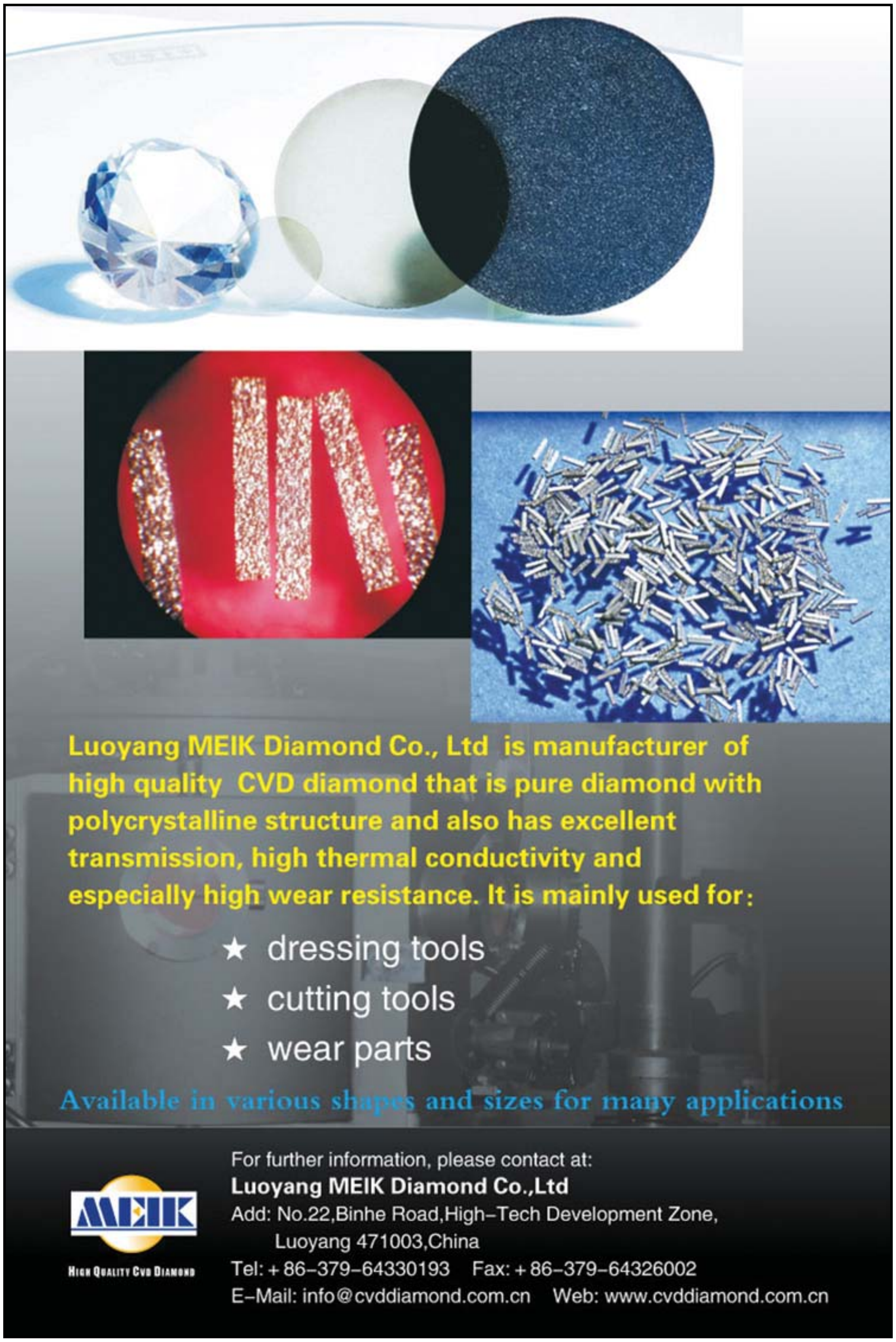

Luoyang MEIK Diamond Co., Ltd is manufacturer of high quality CVD diamond that is pure diamond with polycrystalline structure and also has excellent transmission, high thermal conductivity and especially high wear resistance. It is mainly used for:

- ★ dressing tools
- ★ cutting tools
- ★ wear parts

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which using experimentally measured tool force data, predicts the evolution in the torque and forces acting on the bit. The model permits the design of milling bits so as to provide a uniform cutting load on all cutters and to minimise the variation in bit torque and forces so as to minimise forced drill string vibrations.

Laboratory Metal-Cutting Tests and Tool Wear Performance

It will be evident from Figure 1 that each cutter on the bit experiences an interrupted cut. In the very first and last stages of the exit window milling process, cutters are engaged for up to (approximately) one third of a revolution, while for the majority of the process, cutters are engaged in the liner for a distance approximately equal to tube wall thickness (or about 20 degrees of rotation). This is considered a key aspect of the process, which would be overlooked in the more typical continuous cutting tests, employed in metal cutting research. Therefore and in an effort to use the actual duplex stainless steel liner pipe used in the field, an eccentric face-turning arrangement was devised in which the tube is clamped off-centre in the chuck of a CNC lathe and the tool fed across the face with a constant cutting speed, depth of cut and feed. The test arrangement is illustrated in Figure 2.

Three classes of cutting tool material were assessed for their wear performance in turning duplex stainless steel tubes. Polycrystalline diamond (PCD) was an obvious candidate given that in the field, the bit must also resist the abrasion demand imposed by the rock. The PCD grade employed has a course grain multi-modal grain structure and is somewhat similar to the PCD materials used for drag bits. A commonly used grade of carbide for machining stainless steels was also assessed, as was a polycrystalline cubic boron nitride material with a high CBN-content and a fine grain size. In the present context, high-CBN content PCBN may be considered to have a balance of properties between diamond and cemented carbide and such materials are normally employed for the machining of hard and/or abrasive steels and cast irons. All materials were tested in the form of RNMN090308 inserts (or 3/8 inch round buttons) with different edge preparations. Cutting speeds for the tests were varied; from values typically used for machining duplex steels in the laboratory ('medium') to speeds above ('high') and below ('low') such values. For combinations of cutting tool material, edge preparation and cutting speed, two values of feed were used, 'high' and 'low'. All cutting tests were undertaken with flood cooling using an emulsion of oil and water. The basic methodology employed to assess a tool material suitability for cutting duplex stainless steel was to machine across the face of the tube for a fixed number of passes. The three components of the force were acquired in each test using a Kistler platform dynamometer. Wear measurements were undertaken with an optical microscope with a micrometer measuring stage.

For the high and medium values of cutting speed, excessive wear was observed on all cutting tool materials. The carbide and PCBN tools generally exhibited excessive chipping due to adhesion between the chip and the tool. While adhesion was less of an issue for the PCD tools, only at the lowest cutting speed did an acceptable level off wear occur. Due to the degree of damage incurred on the carbide and PCBN tools and the fact that such materials would fair poorly in rock cutting, further wear testing was limited to PCD tools, exploring lower cutting speeds, different edge preparations and feed values.

Measurement of Tool Forces

The eccentric face-turning test outlined above is clearly very different to real-life exit window milling processes, not only in terms of kinematics and dynamics but critically, in that it is based on fixed displacement of the cutting tool. In the field, apart from more complex kinematics and dynamics, the bit will progress through the liner at a rate determined by the weight on bit; or nominally fixed load conditions. With regard to the objective of this work to provide a modelling tool for process optimisation, fixed load simulation was considered to be of excessive complexity and a fixed displacement model was developed on the basis that such simulations under different boundary conditions would permit sufficient insight into fixed load milling processes. In order to develop the model, it was necessary to acquire tool force data under several different cutting conditions. The manner in which force data for stationary single point tools is treated so as to be relevant to a multi-cutter rotary milling tools is outlined in Section 4. In this section, we present the force components – as-measured in the eccentric face-turning test – as a function of edge preparation, cutting speed and feed; depth of cut was constant. The three orthogonal force components are the cutting force (acting parallel to the cutting velocity vector), the thrust force (acting parallel to the depth of cut setting direction) and the feed force (acting parallel to the feed direction). Figure 3 shows the tool force data for PCD tools with different edge geometries, all for the cutting speed which gave the lowest level of wear. It is evident that of the three edge geometries tested, the up sharp edge results in the lowest initial force, but the largest increase due to wear. Conversely, the most negative geometry results in the largest initial force but the smallest increase due to wear. Similar levels of flank wear were measured on all three tools. For the up sharp tool, the initial cutting force is greater than the initial thrust force, whereas the opposite is the case for the chamfered tools. A practical consequence therefore, of using chamfered tools under fixed load conditions is that the cutter will penetrate the workpiece more slowly. Figure 4 shows the influence of cutting speed on tool forces, all for edges with a medium chamfer and for a fixed value of feed. Interestingly, the lower

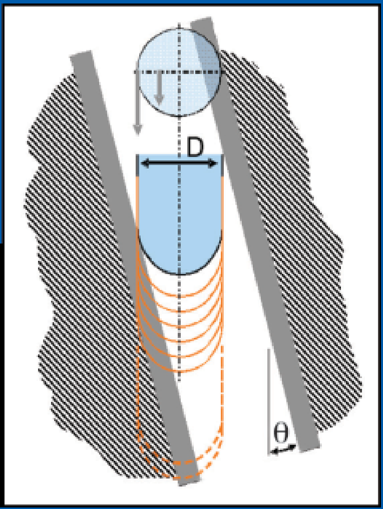

FIGURE 1 – ***Illustration of the exit window milling process in which a bit is fed along an inclined path into the steel liner of the well bore.***

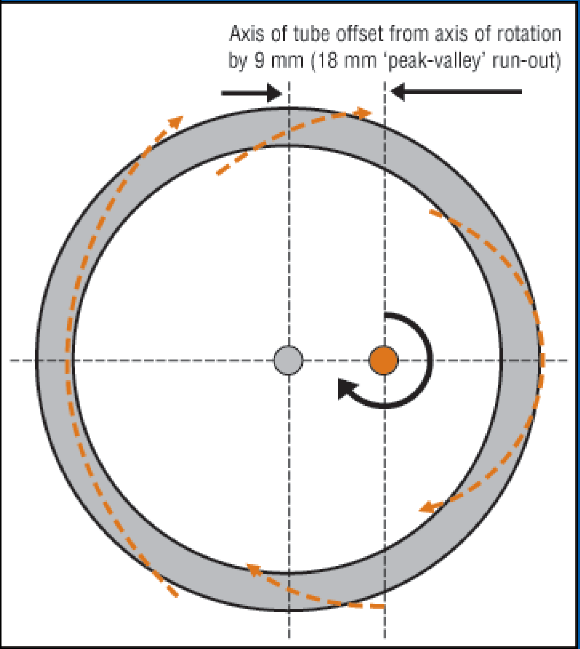
Axis of tube offset from axis of rotation
by 9 mm (18 mm 'peak-valley' run-out)

FIGURE 2 – ***Eccentric, interrupted face-turning arrangement (as viewed along the axis of the chuck and tube) which imposes varying engagement times on the cutting tool as it is fed across the face of the tube. The broken red lines exemplify cutter paths at three stages within one pass.***

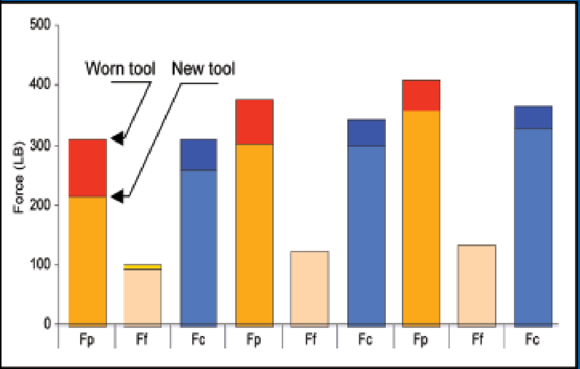

FIGURE 3 – ***Tool forces for PCD RNMN0903 cutters with different edge geometries. The lower portion in each column indicates the magnitude of the force for a new (unworn) tool and the upper portion, the increase due to wear. All cutters were used for just two passes across the tube face.***

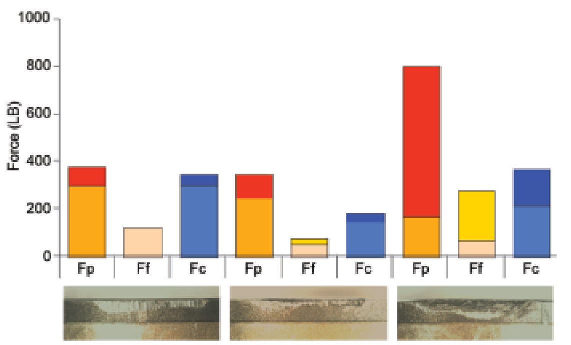

FIGURE 4 – ***Influence of cutting speed on force components for PCD RNMN0903 cutters with medium chamfered edges. The PCD layer thickness on all cutters is 0.02 inch.***

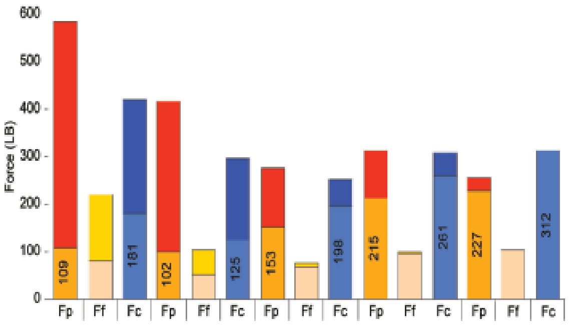

FIGURE 5 – ***Influence of feed on force components for PCD RNMN0903 cutters with a medium chamfer and with the lowest cutting speed evaluated. The feed values are indicated as a percentages (note the centre-most columns have a feed of 100%).***

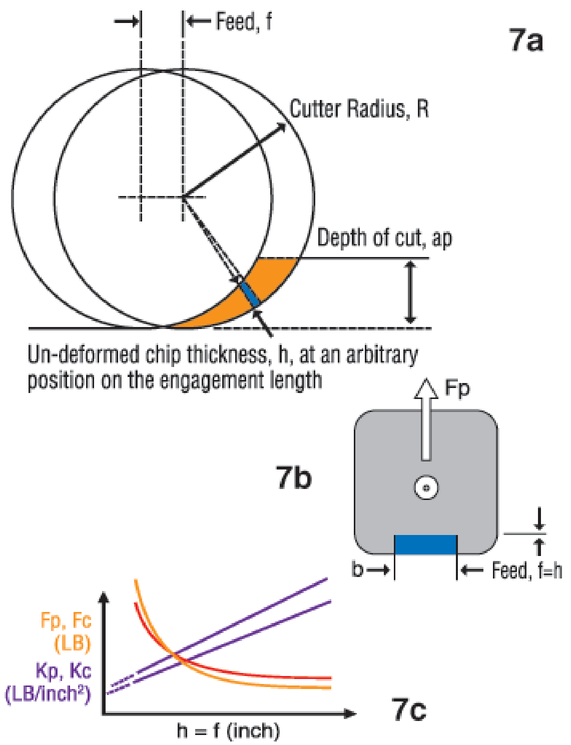

FIGURE 6 – ***(a) The un-deformed chip geometry when machining with round tools. (b) An 'orthogonal' cutting arrangement in which a rectangular un-deformed chip geometry is realised and (c), the type of relationships observed in orthogonal cutting.***

the cutting speed, the higher the initial thrust, cutting and feed force acting on the tool. At the highest speed, the four-fold increase in thrust force over two passes of the workpiece is due to catastrophic edge chipping. Although, the lowest tool forces (after two passes) are apparent at a medium cutting speed, the edge definition is poor. The edge tested at the lowest speed - though resulting in a slightly higher thrust force – is considered to exhibit a more favourable state of wear.

All three edges shown in Figure 4 have removed the same stock from the duplex stainless steel tubular workpiece, albeit at different rates. The stock is simply the product of the feed, the depth of cut and the total sliding distance of the tool against the workpiece. As the wear experienced by the tool shows a fairly linear dependence on the sliding distance (for a given cutting speed), increasing either or both feed and depth of cut is expected to effect greater stock removal for the same level of wear. Figure 5 shows the influence of feed on the tool forces for a fixed depth of cut. As would be expected, the higher the feed, the higher the initial force (acting on the unworn tool). However, the increase in force after two passes is very much greater for the smaller values of feed – this is a consequence of the longer sliding distances (over two passes across the face of the tube) and therefore greater levels of wear. While it may be correctly argued that the maximum chip area (i.e., product of feed and depth of cut) will be limited by the available torque or spindle power, equal emphasis must be placed on the magnitude of the increase in tool forces – ultimately, the increased torque demand due to higher levels of wear may far outweigh the initially lower forces. Considering also the influence of cutting speed, the ideal combination of cutting conditions for cutting duplex stainless steel with PCD is a very low speed and a high feed (and depth of cut).

Modelling of the Exit Window Milling Process

For a single-point tool engaging a workpiece at a given cutting speed, irrespective of process kinematics, the resultant, instantaneous force on the tool is determined by the area of engagement (or specifically, the un-deformed chip cross sectional geometry) and the level of wear on the tool. Therefore, modelling of the tool forces firstly requires the means to calculate the un-deformed chip geometry and secondly, to know the relationship between un-deformed chip thickness and tool force. The former is an exercise in geometry while the latter is experimentally determined. Section 4.1 explains how the forces acquired in the current experimental work are used to derive a 'force model' (in practice a series of equations) for PCD cutting duplex stainless steel. For a multi-cutter tool or bit, the resultant force on the tool is simply the summation of forces acting on each of the cutters. The principle task is therefore to model the helical path of each cutter comprising the bit and critically, the transient surface generated on the workpiece, which must be known so as to predict the un-deformed chip geometry (noting the free surface of the workpiece defines one boundary of the un-deformed chip cross-section). Section 4.2 outlines the approach taken to 'geometrical modelling' in the current work.

Force Model for PCD-Duplex Stainless Steel

Immediately above, we refer to 'un-deformed chip thickness' and 'un-deformed chip crosssectional geometry'. Modelling of tool forces is little more than the distinction between the two quantities. Firstly, note thickness is a one-dimensional quantity, while shape is twodimensional. With reference to Figure 6a, the un-deformed chip geometry generated by two over-lapping circles separated by the feed dimension, is determined by the circle radius, R, the feed, f and the depth of cut, ap. The un-deformed chip thickness, one particular value exemplified by the small blue rectangle, varies continuously along the engagement length. If, as is possible in 'orthogonal' cutting experiments1, one realises an un-deformed chip thickness of uniform dimensions along the entire engagement length (i.e., a rectangular un-deformed chip geometry as shown in Figure 6b), one may determine the relationship between un-deformed chip thickness and the thrust and cutting forces and this will resemble the blue curve in Figure 6c; note the intercept at h = 0 is non-zero. If the measured forces are normalised by the chip area, one obtains the 'specific forces' Kp and Kc (which despite the term are actually stresses). These curves are reasonably well modelled using a power function such as Kc = C1.hC2 and Kp = C3.hC4. While C1 – C4 may be thought of as constants for a given tool-workpiece pair and given cutting speed and tool edge geometries, they are also sensitive to the level of tool wear. Therefore, a complete force model requires at least another four 'constants', C5 – C8, determined using a tool with a defined level of wear.

	C1 (LB/in^4)	C2 ( )	C5 (LB/in^4)	C6 ( )
Kc (LB/in^2)	76870	-0.36	21476	-0.6

TABLE 1 – ***Constants relating specific cutting force to un-deformed chip thickness, h through a power function; Kc = C1.hC2 for an unworn tool and Kc = C5.hC6 for a worn tool.***

While the orthogonal cutting method has been used to explain the method of modelling tool forces, it is possible to extract the same equations for Kc and Kp from conventional turning tests with round tools and by doing so, the constants listed in Table 1 have been determined.

Note, only the Kc values are provided so as to indicate the magnitude of the quantities involved.

Geometrical Modelling for Inclined Exit Milling Process

A single cutter on a rotating bit which is fed (or translated) at a constant speed will trace a helical path in 3D space. The intersection of this rotating and translating cutter with a planar surface will essentially represent the un-deformed chip geometry. Where several cutters are present in the bit, there will be multiple cutter-workpiece engagements per revolution. The principle difficulty in modelling the advance of a rotating bit at a slight angle to the internal bore of a tube (as is the exit window milling process illustrated in Figure 1) is related to the generation of the transient machined surface, which comprises a multitude of overlapping feedmarks. The transient machined surface is important as it, along with the cutter position and diameter, determine the un-deformed chip geometry. The algorithm developed in the present work is outlined in Figure 7. The bulk of the computational effort is in determining the un-deformed chip geometry for all cutters on the bit as a function of rotational angle and the bit position on the linear feed trajectory. Once determined, the instantaneous chip geometry for each cutter is approximated as neighbouring rectangular sections (as suggested in Figure 6a) and the forces acting on each discrete sections calculated using the force model, as represented in part by the data in Table 1. Vector summation of the forces acting on each discrete section of chip provides the resultant force on each cutter. In turn, vector summation of the orthogonal force vectors acting on each cutter in the bit provides the bit torque and forces. As for the experimental cutting tests, the model is based on fixed displacement rather than fixed load (or in field terminology, fixed weight on bit). The following section of this paper provides examples of the output of the model.

Example Output From Exit Window Modelling Program

In the present example, a simple, non-optimized, bit design is used whereby 15 cutters are arranged on six blades so as to provide a fairly uniform distribution of cutting edges along the periphery of the bit. The incline angle, θ (as illustrated in Figure 1), was set at 20, the linear feed rate of the bit was set at values of 0.02 and 0.04 inch (0.5 and 1.0 mm) per revolution (two different simulations). Taken from the simulation with a linear feed rate of 0.02 inch, Figure 8 shows the transient inner surface of the tube after the bit has penetrated 0.04 inch (in the direction normal to the tube axis) after just over 100 revolutions of the bit. Note, the surface is unfolded for ease of viewing and only 180 degrees of the tube is shown as the other side is un-touched by the bit. On the left of the plot, one may observe that only four cutters on the bit are engaging the tube at this stage of the process. Also, one may note that for the leading (leftmost) cutter, the simulation has paused at an angular position of 900 such that the un-deformed cross section is evident (indicated by the arrow).

Taken again from the simulation with a feed rate of 0.02 inch, Figure 9 shows the evolution in the torque acting on the bit from the point of initial engagement to the point at which the bit penetrates the outside surface of the tube wall. In this plot, the near-horizontal axis represents the bit angular position (ranging from 0°-359°) and the near-vertical axis, the bit progression in mm. The plot is color coded according to the legend and the values are expressed in N.m (1 N.m equalling 0.74 ft.LB torque). It may be seen that a peak torque of over 360 N.m (266 ft.LB) occurs when the bit is at its maximum point of immersion in the tube (however, the average torque within the final revolution is lower). With further progression of the bit through the tube wall, the torque and forces applied to the bit by the steel tube will decrease, although the bit will most likely experience an increased overall load due to immersion in the rock.

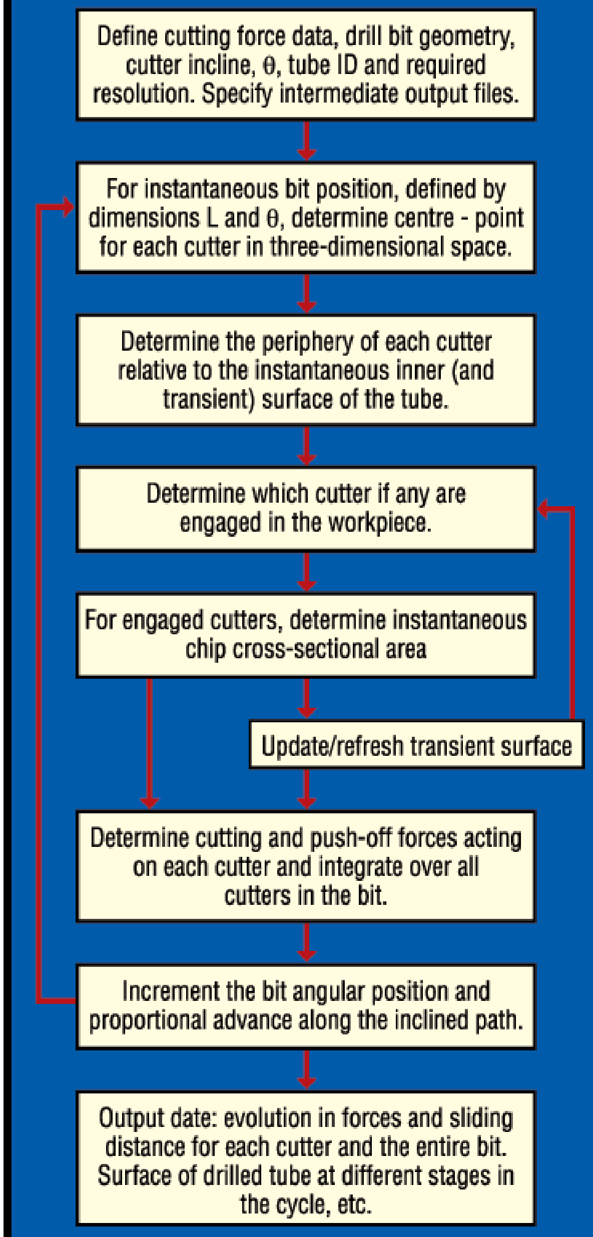
Define cutting force data, drill bit geometry, cutter incline, θ, tube ID and required resolution. Specify intermediate output files.
For instantaneous bit position, defined by dimensions L and θ, determine centre - point for each cutter in three-dimensional space.
Determine the periphery of each cutter relative to the instantaneous inner (and transient) surface of the tube.
Determine which cutter if any are engaged in the workpiece.
For engaged cutters, determine instantaneous chip cross-sectional area
Update/refresh transient surface
Determine cutting and push-off forces acting on each cutter and integrate over all cutters in the bit.
Increment the bit angular position and proportional advance along the inclined path.
Output date: evolution in forces and sliding distance for each cutter and the entire bit. Surface of drilled tube at different stages in the cycle, etc.

FIGURE 7 – ***Algorithm for modelling of the exit window milling process.***

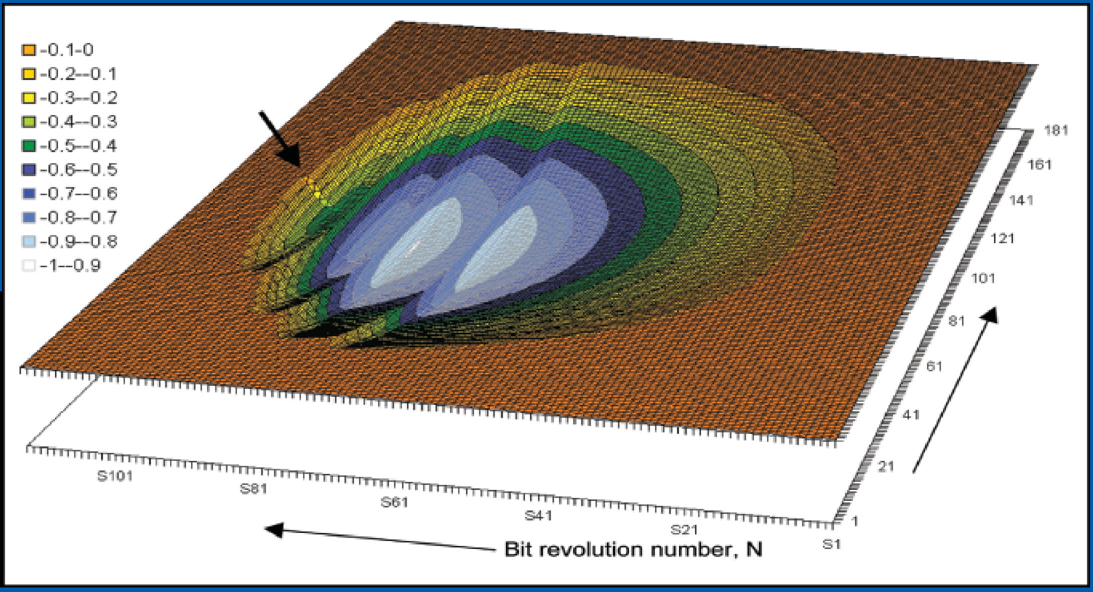

FIGURE 8 – ***The transient inner surface of the tube after the bit has penetrated to a depth of 0.04 inch. The surface plot is color coded (note legend, where the units are in mm and the values negative). The feed rate for this simulation was 0.02 inch/revolution.***

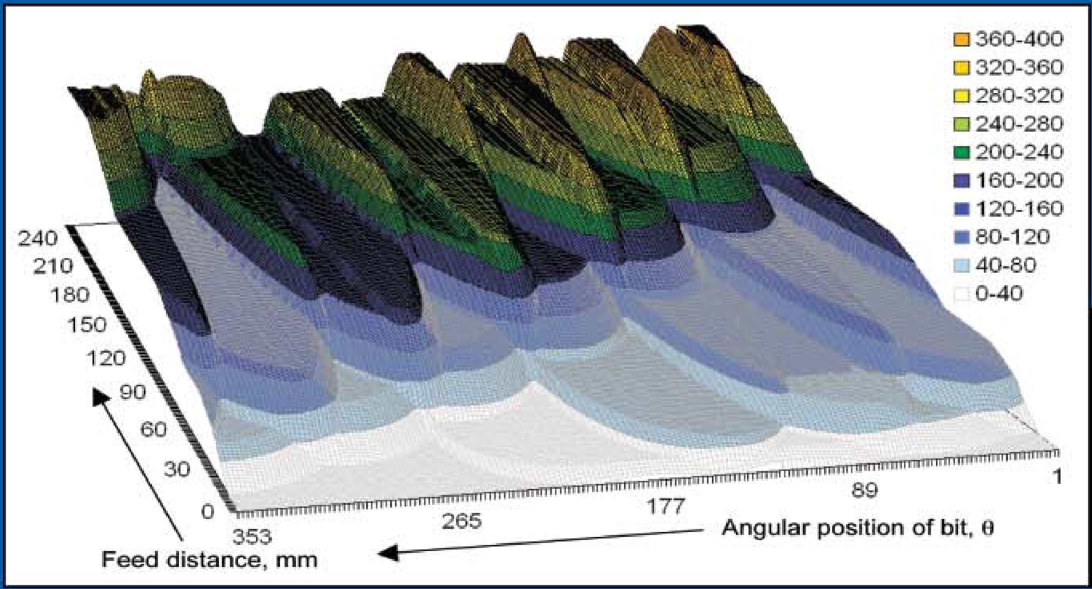

FIGURE 9 – ***Torque evolution on bit during the penetration of duplex stainless steel liner tube. The torque values are indicated by the legend and are expressed in mm (1 N.m = 0.74 ft.LB). The feed rate for this simulation was 0.02 inch/revolution.***

Summary and Conclusions

The goal of this work was to develop a series of guidelines to improve the efficiency of exit window milling in well bore lining tubes for oil and gas production. Having assessed the suitability of PCD, PCBN and carbide cutters for the machining of duplex stainless steel using a novel, eccentric face-turning arrangement with tubular workpieces, near-optimum cutting conditions have been established. The same cutting experiments provided accurate tool force data, which was mathematically modelled so as to permit the calculation of forces for un-deformed chip cross-sections of arbitrary geometry – a fundamental requirement for the geometrical modelling of the exit window milling process. A geometrical model based on steady-state cutting with defined feed rates of the bit was developed in which the instantaneous chip load on each cutter is calculated as a function of bit rotational and translational position. Cutter wear is also accounted for in the model. Summation of the orthogonal forces acting on each cutter provides the overall torque and axial force (the latter representing a similar quantity as weight on bit) at every instance during the process. The model permits the simulation of different bit geometries and cutting conditions. The principle outputs of the geometrical model are the evolution in the bit torque and axial force as the bit penetrates the tube wall. Simulations using different bit configurations and cutting conditions provide insight to the interrelationships that exist in the process. An example of such is provided in this article and the results suggest that the most efficient way in which penetrate the lining tube wall is with as high a feed rate as possible and with very low bit RPM – the key challenge however, is marrying the idealized findings from the lab with real-life limitations on bit torque, stability and process control.

The increasing torque on the bit as it progresses through the tube wall is due to increasing chip loads and increasing wear on each of the 15 cutters. If there were no wear on the cutters, the torque values would be less than half those shown in Figure 9. The simulation from which the data in Figures 9 & 10 was taken also provided the orthogonal forces acting on the bit, the most critical of which is the 'axial force'; i.e., the force acting to push the bit back up the tube bore (which is a comparable quantity to the weight on bit, 'WOB'). The same simulation as described above (with a feed rate of 0.02 inch/revolution or 0.5 mm/revolution) was also run with a feed rate of 0.04 inch/revolution (or 1.0 mm/revolution). From the two simulations, the average torque and axial force or WOB values for each revolution of the bit were determined and these are shown in Figure 10.

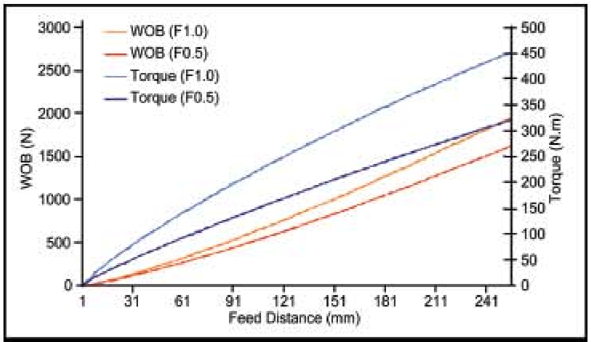

FIGURE 10 – ***The evolution in average axial force, labelled as 'WOB', and torque during each revolution as a function of linear feed distance. Penetration of the tube wall occurs just after 250 mm (8 inch) linear feed of the bit.***

The single-most important feature of the results in Figure 10 is the fact the lower linear feed rate results in torques and forces that are 70 – 80% of those generated with double the feed rate. Not only does the higher feed rate result in tube penetration in half the time, the cutters experience less wear. Were data generated after a linear displacement of about 16 inch (500 mm), the WOB or axial force for both feed rates would be near identical. Interestingly, one may note that there is a greater difference in the torque for the two sets of simulation conditions. The torque requirement is principally determined by the forces acting parallel to the cutting velocity vectors whereas the resultant axial force on bit values are principally determined by the forces acting in the plane of the cutter rake face – forces which happen to be more sensitive to tool wear. Therefore, in machining duplex stainless steel with PCD, cutter wear has a greater influence on the axial force than it does on the bit torque. It is worth noting also, that the principle phenomenon governing the shape of the curves in Figure 10 is the size effect. In the real-life process where a fixed weight on bit is applied, the situation is more complex and the penetration rate of the bit through the tube wall is likely to be initially quite high but rapidly reducing as the chip load and the cutter wear flats increase in size. In addition, impact loading of cutters due to drill string vibrations and bit-whirl introduce the possibility of catastrophic failure of cutters. Nonetheless, it is believed that the ability to simulate exit window milling processes using accurate force models provides insight into the interrelations which exist between bit design, process kinematics and cutter wear – the remaining challenge is to incorporate real life process dynamics, however, this is likely to increase model complexity by an order of magnitude.that the most efficient way in which penetrate the lining tube wall is with as high a feed rate as possible and with very low bit RPM – the key challenge however, is marrying the idealized findings from the lab with real-life limitations on bit torque, stability and process control. ■

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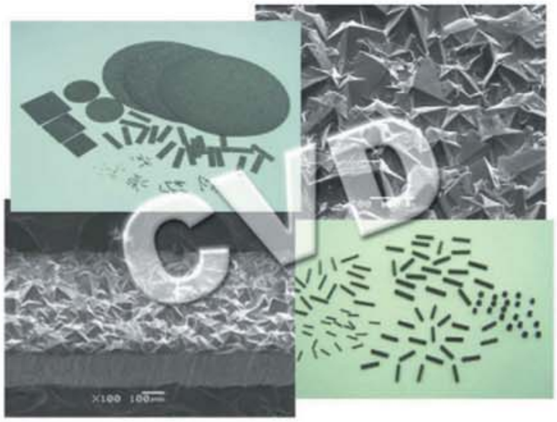

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High Wear Resistance and High Strength PCD Tools to Increase Productivity and Improve Machining Accuracy

Sumitomo Electric Hardmetal Corp.
CBN-Diamond Products Group
Super Hard Materials Development Department
Tomohiro Fukaya

NEW PCD TOOLS DEVELOPED TO RESPOND TO MARKET DEMAND

Polycrystalline diamond (PCD) tools have been used world-widely in the machining of non-ferrous materials such as aluminum alloy or copper alloy.

To respond to a market demand for higher wear-resistance and higher strength PCD tools that can increase productivity and improve the machining accuracy of hard to cut work materials, new PCD tools were developed. The diamond content of this PCD is very high with fine grain size diamond, so it gives a longer tool life with higher machining efficiency and better machining accuracy in the applications in which conventional PCD tools wear rapidly or have edge chipping. Diamond has superior characteristics, such as being the hardest material, and possessing the highest Young's modulus and high thermal conductivity. PCD tools manufactured by sintering diamond powder with Co binder metal are widely used in various industries for cutting tools of nonferrous metals and nonmetals. In 1998, high strength PCD tools, which have high diamond content and fine grain size diamond, were developed to increase machining efficiency, especially in the roughing of non-ferrous metals.

Recently, to improve the performance of manufactured products, such as automobiles, work materials have had a tendency to be harder to cut. There has also been a demand for better accuracy and closer tolerances of the final parts. Further more, to increase the productivity and reduce the manufacturing cost, cutting speeds are increasing. As a result of these trends in machining, there is a growing need for PCD tools with higher wear resistance and higher strength. To respond to such needs, a new PCD tool was developed.

	PCD-A	PCD-B	PCD-C	PCD-D	PCD-E
Grain size (μm)	up to 0.5	0.5	0.5	5	50
TRS (GPa)	2.60	2.45	2.15	1.95	1.10

Table 1: Features of PCD Tools

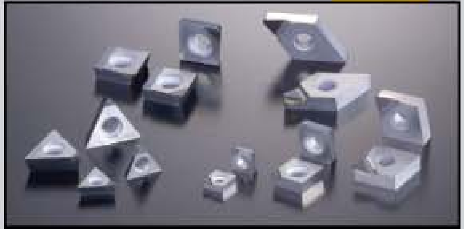


Figure 1: High-Wear Resistance High Srength PCD Tools

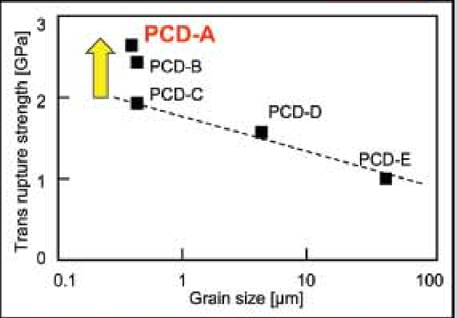


Figure 2 Grain Size and Trans Rupture Strength

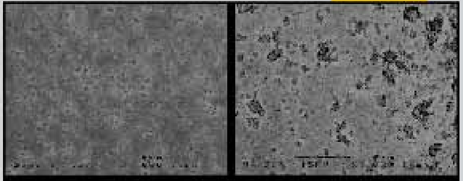


Figure 3: Microstructure of PCD (after acid treatment)

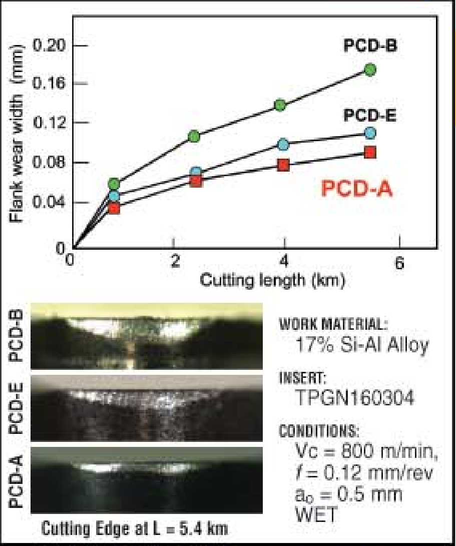


Figure 4: Flank-Wear Width in 17% Si-Al Alloy Turning

FEATURES OF NEW PCD TOOLS

New PCD tools are shown in Fig. 1, and the features of the PCD tools are shown in Table 1. PCD-A is the new PCD tool and the others are conventional PCD tools. Fig. 2 shows the relationship between the grain size and transverse rupture strength of PCD. Generally finer grain size PCD shows higher transverse rupture strength. Coarse grain size PCD-E shows the lowest transverse rupture strength and that of PCD-C with fine grain size diamond is 2.15 GPa. PCD-B developed in 1998 shows higher transverse rupture strength, 2.45 GPa, than PCD-C in spite of the same grain size as PCD-C. It is because the diamond content of PCD-B is higher than that of PCDC. The new PCD tool, PCD-A, shows the highest transverse rupture strength, 2.60 GPa, among all of the PCD tools. This remarkable strength was achieved by increasing the diamond content with finer grain size diamond than that of PCD-B. To compare the diamond content of PCD-A and PCDB, the microstructures were observed after acid treatment. The results are shown in Fig. 3. The Co binder phase was leached out by acid treatment, and it was clear that the diamond content of PCD-A is higher than that of PCD-B.

CUTTING PERFORMANCE EVALUATION

The diamond content of PCD-A is very high with fine grain size diamond, so better wear resistance and less chipping was expected. To evaluate the wear resistance of PCD-A, a cutting test was carried out with hard to cut aluminum alloy. Work material was high silicon aluminum alloy (17% - Si) and cutting speed was 800 m/min. The test results are shown in Fig. 4. PCD- A shows the better wear resistance than not only PCD-B but also PCD-E, 50μm coarse grain size PCD. V-T curve in the turning of 17 % Si-Al alloy is shown in Fig. 5. PCD-A shows longer tool life than that of PCD-E in the cutting speed 200 to 800 m/min. Before the development of PCD-A, coarse grain size PCD-E was recommended to high Si-Al alloy machining, because it showed the best wear resistance. The strength of coarse grain size PCD-E was low and the cutting edge easily chipped, so there were some difficulties in the machining of high Si-Al alloy. It is expected that the excellent wear resistance better than coarse grain size PCD and higher strength better than conventional fine grain size PCD of PCD-A will solve such difficulties.

PCD-A also shows excellent performance in the machining of 12% Si-Al alloy. Cutting test results is shown in Fig. 6. PCD-A shows the best wear resistance among the PCD tools. PCD-A has high strength, so it shows long and stable tool life in the milling applications.

Fig. 7 shows the test results of milling of 12% Si-Al alloy. In this test the flank wear width of conventional PCD-B was increased due to the micro chipping of the cutting edge after cutting volume 2,600 cm3. The cutting edge strength of PCD-A is better than that of PCD-B, so micro chipping did not occur in the cutting edge of PCD-A and the wear resistance of PCD-A was better than that of PCD-B. Furthermore, PCD-A is suitable for the high precision machining of nonferrous metals.

Comparison of machined surfaces of PCD-A and PCD-D are shown in Fig. 8 and the SEM images of the end cutting edge of these inserts are shown in Fig. 9. The surface roughness of PCD-A was 3.6 μm and it was better than that of PCD-D, 5.8μm. The feed mark of PCDA was smooth but that of PCD-D had some irregularities. It is because that the cutting edge of fine grain size PCD-A was smooth but that of PCD-D was not smooth due to the 5μm diamond particle size. Nowadays, the required surface finish of work parts is getting much better, and PCD-A shows excellent surface finish in such high precision applications.

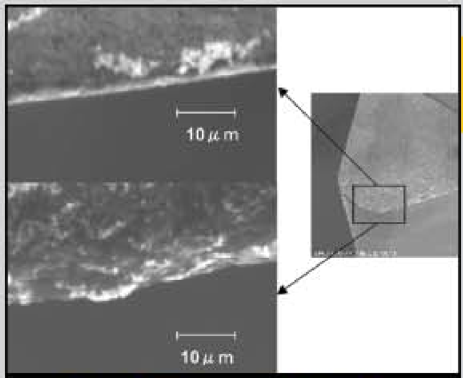
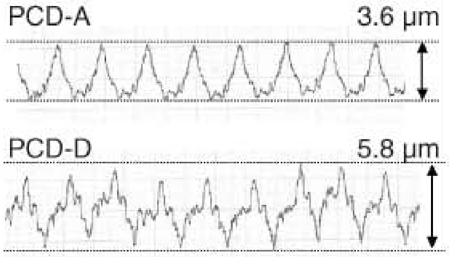


Figure 9: SEM Images of the Cutting Edge

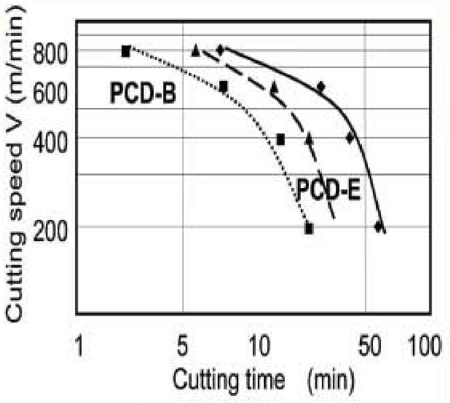


WORK MATERIAL: 17% Si-Al Alloy
NSERT: TPGW160308
CONDITIONS: Vc = 1,000 m/min,
a_p = 0.2 mm,
f = 0.15 mm/rev, WET

Figure 8: Comparison of Machined Surface

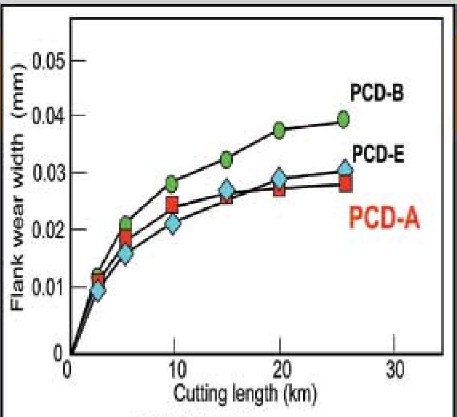
APPLICATION EXAMPLES

PCD-A has shown excellent performance in many applications. Fig. 10 shows the application example of boring of bushing made of copper alloy that is hard to cut. Criterion was surface roughness of Rz 3.2 μm. In this application, the tool life of conventional PCD-B was only 800 pieces due to the severe chipping at the cutting



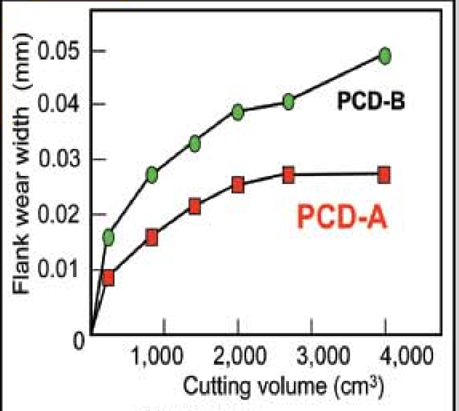
WORK MATERIAL: 17% Si-Al Alloy
INSERT: TPGN160304
CONDITIONS: Vc = 200-800 m/min, a_p = 0.5 mm,
f = 0.12 mm/rev, WET
CRITERION: Vb = 0.1 mm

Figure 5: V-T Curve of PCD Tools



WORK MATERIAL: 12% Si-Al Alloy
NSERT: TPGN160304
CONDITIONS: Vc = 2,000 m/min,
a_p = 3.0 mm,
f = 0.15 mm/rev, WET

Figure 6: Flank-Wear Width in 12% Si-Al Alloy Turning



WORK MATERIAL: 12% Si-Al Alloy
INSERT: NF-SNEW1204ADFR
CUTTER: RF4100R (6-flute)
CONDITIONS: Vc = 2,000 m/min, a_p = 3.0 mm,
f = 0.15 mm/rev, WET

Figure 7: Flank-Wear Width in 12% Si-Al Alloy Milling

Calendar of EVENTS

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22 Performance Racing Industry
DECEMBER 10-12, 2009
Thursday, Friday, and Saturday
ORLANDO, FLORIDA · USA
Orange County Convention Center · North/South Building

December 10-12, 2009
Performance Racing Industry
Orlando, Florida, USA
Orange County Convention Center
www.performanceracing.com

CALENDAR EVENTS for 2010

February 2-5, 2010
World of Concrete
Las Vegas Convention Center
Las Vegas, NV
www.worldofconcrete.com

February 9-11, 2010
Medical Design & Manufacturing Show
Anaheim Convention Center,
Anaheim, California USA
http://www.MDMWest.com

March 2, 2010
International Screw-Cutting Machine Tool Show
Parc des Expositions
la Roche-sur-Foron, France
www.rochexpo.com

March 2-7, 2010
CSDA 2010 Convention
Loews Coronado Bay Resort
Coronado, CA
www.csda.org

May 5, 6 & 7, 2010
Industrial Diamond Association
ANNUAL MEETING
Hilton Columbus at Easton
Hotel • Columbus, Ohio
www.superabrasives.org

March 23-25, 2010
Westec
L.A. Convention Center
Los Angeles, California
westeconline.com

April 12-16, 2010
International Wire and Cable Trade Fair
Dusseldorf Exhibition Centre
Düsseldorf, Germany
http://www.mdna.com/

April 14-15, 2010
MicroManufacturing Conference & Exhibits
Hilton Phoenix East/Mesa
Mesa, Arizona
http://www.sme.org/cgi-bin/get-event.pl?--001874-000007-mhome--SMEJune

June 8-9, 2010
Medical Design & Manufacturing Show - EAST
Jacob K. Javits Convention Center
655 W. 34th St. (W. 34th St. at 11th Ave.)
New York, NY
http://www.devicelink.com/expo/east09/

June 14-18, 2010
CIMES
New China International Exhibition Center
Tianzhu Airport Industrial and Commercial Zone in Shunyi District
Beijing, China
www.cimes.net.cn/en/

September 29-30, 2010
Innovative Manufacturing Summit
Drury Lane Convention Center
Oak Brook Estates, IL
www.sme.org/advantage

October 20-21, 2010
Innovative Manufacturing - Aerospace/Defense
Gaylord Palm Hotel & Convention Center
Kissimmee, FL
www.sme.org/newevents

CALENDAR EVENTS for 2011

May, 2011
Industrial Diamond Association
ANNUAL MEETING
April 30 & May 1, 2011
Hyatt Regency O'Hare
Chicago, Illinois
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Watch for Details

INTERTECH 2011

May 2-4, 2011
Hyatt Regency O'Hare
Chicago, Illinois

INTERTECH 2011
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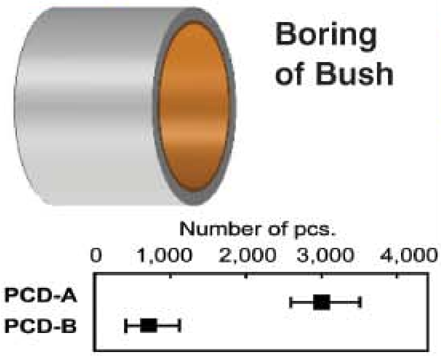
U.S. Diamond Sawblades Industry Vows to Fight Fraudulent Circumvention of the Antidumping Duty Orders on China and Korea

December 14, 2009 Contact: Daniel B. Pickard 202.719.7285 dpickard@wileyrein.com Washington, DC – Today, counsel for U.S. producers of diamond sawblades announced that they have identified certain Chinese producers of diamond sawblades that are marketing their products as free of antidumping duties (or eligible for reduced duties) through a variety of fraudulent schemes that could land importers in hot water for customs fraud violations. Diamond sawblades, diamond segments, and diamond sawblade cores from China are currently subject to antidumping duties of up to 164 percent. Korean sawblades, cores and segments are also subject to duties of up to 26 percent. "We are aware that certain producers in China are attempting to illegally circumvent the antidumping duty order," said Daniel B. Pickard, a partner in Wiley Rein's International Trade Practice and counsel U.S. diamond sawblades industry. "The U.S. industry is committed to ensuring that circumvention is prevented, and that fraudulent importations are prosecuted to the fullest extent of the law. Importers should be aware that some exporters are misrepresenting the applicable duty rates, or even encouraging importers to defraud the government." Information presented to the U.S. Bureau of Customs and Border Protection strongly indicates that Chinese producers of diamond sawblades are engaged in a variety of schemes aimed at misleading importers and other purchasers as to the magnitude of the duties involved, or attempting to convince importers to commit customs fraud in order to avoid them. Under Customs' enforcement procedures, it is importers, rather than exporters, who must pay all duties, including any fines and penalties that arise from antidumping duty circumvention on the part of foreign producers and exporters.

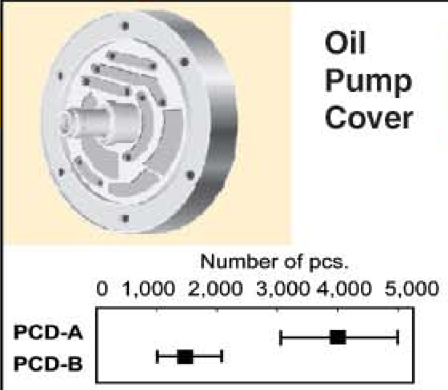
One prevalent scheme includes misinforming potential importers that the Chinese producer or exporter's antidumping duty rate is far lower than it actually is, potentially subjecting the importer to large and unforeseen duty liabilities. In other instances, Chinese producers and exporters are encouraging importers to commit both classification and valuation fraud by importing the merchandise under inappropriate tariff provisions, or altering invoices and Customs documentation to reflect a price lower than the price at which the merchandise is actually being sold. Such fraud subjects importers to potential criminal penalties, including fines and jail time, and civil penalties of up to twice the value of the lost duties. "We urge purchasers dealing with producers in China and Korea to be aware of these schemes, and not to simply take a supplier's word that duties don't apply or can easily be avoided. Circumvention is illegal and can expose purchasers to significant civil and criminal penalties. The U.S. Government has determined that Chinese and Korean diamond sawblades are being sold at dumped prices and threaten material injury to the U.S. producers. We are going to take all appropriate steps to make sure that the antidumping orders are fully enforced," said Pickard.

edge and PCD-A showed 3 times longer tool life than PCDB. PCD-A will solve the difficulties of high precision machining of hard to cut copper alloy. An oil pump cover of 12% Si-Al alloy turning application is shown in Fig. 11. Cutting speed was 1400 m/min and the criterion of this application was no burr generation in the work piece. The tool life of PCD-B was 1500 pieces due to the chipping of the cutting edge and the generation of burr. The tool life of PCD-A was 4000 pieces and 2.7 times longer than that of PCD-B. PCD-A showed excellent wear resistance and strength of cutting edge and suppressed the generation of burr. Fig. 12 shows the 12% Si-Al alloy cylinder block milling application example. The tool failure was the breakage of the cutting edge due to the stress by interruption and the criterion was also the generation of burr in the work piece. The tool life of PCD-A was 70% longer than that of PCD-B. It was due to the high wear resistance and high strength of PCD-A. These application examples indicate that the machining efficiency and tool life can be improved by PCD-A in high speed turning and milling of aluminum alloy parts. High wear resistance and high strength of PCD-A shows excellent performance in high precision machining of non-ferrous hard to cut work materials. PCD-A will contribute to cost reduction and improved productivity. ■



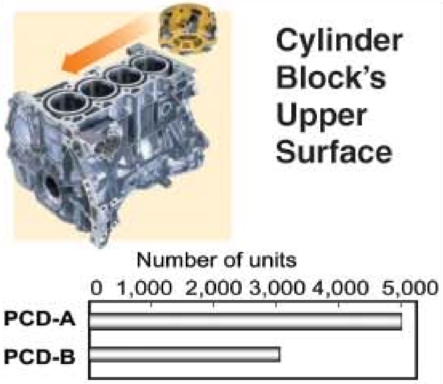
(Cutting length 73 m/piece)
WORK MATERIAL: Copper Alloy
INSERT: TPGN160308
CONDITIONS: Vc = 300 m/min, a_p = 0.08 mm, f = 0.07 mm/rev, WET
SURFACE ROUGHNESS: Rz 3.2 µm

Figure 10: High Precision Boring of Copper Alloy Bush



(Cutting length 62 m/piece)
WORK MATERIAL: 12% Si-Al Alloy
INSERT: CNGX120408
CONDITIONS: Vc = 1,400 m/min, a_p = 0.2 mm, f = 0.3 mm/rev, WET

Figure 11: Turning of 12% Si-Al Alloy Oil Pump Cover



WORK MATERIAL: 12% Si-Al Alloy
CUTTER: RF4200R
INSERT: SNEW1204ADFR
CONDITIONS: Vc = 2,800 m/min, a_p = 2 mm, f = 0.14 mm/rev, WET

Figure 12: Milling of Cylinder Block of 15% Si-Al Alloy

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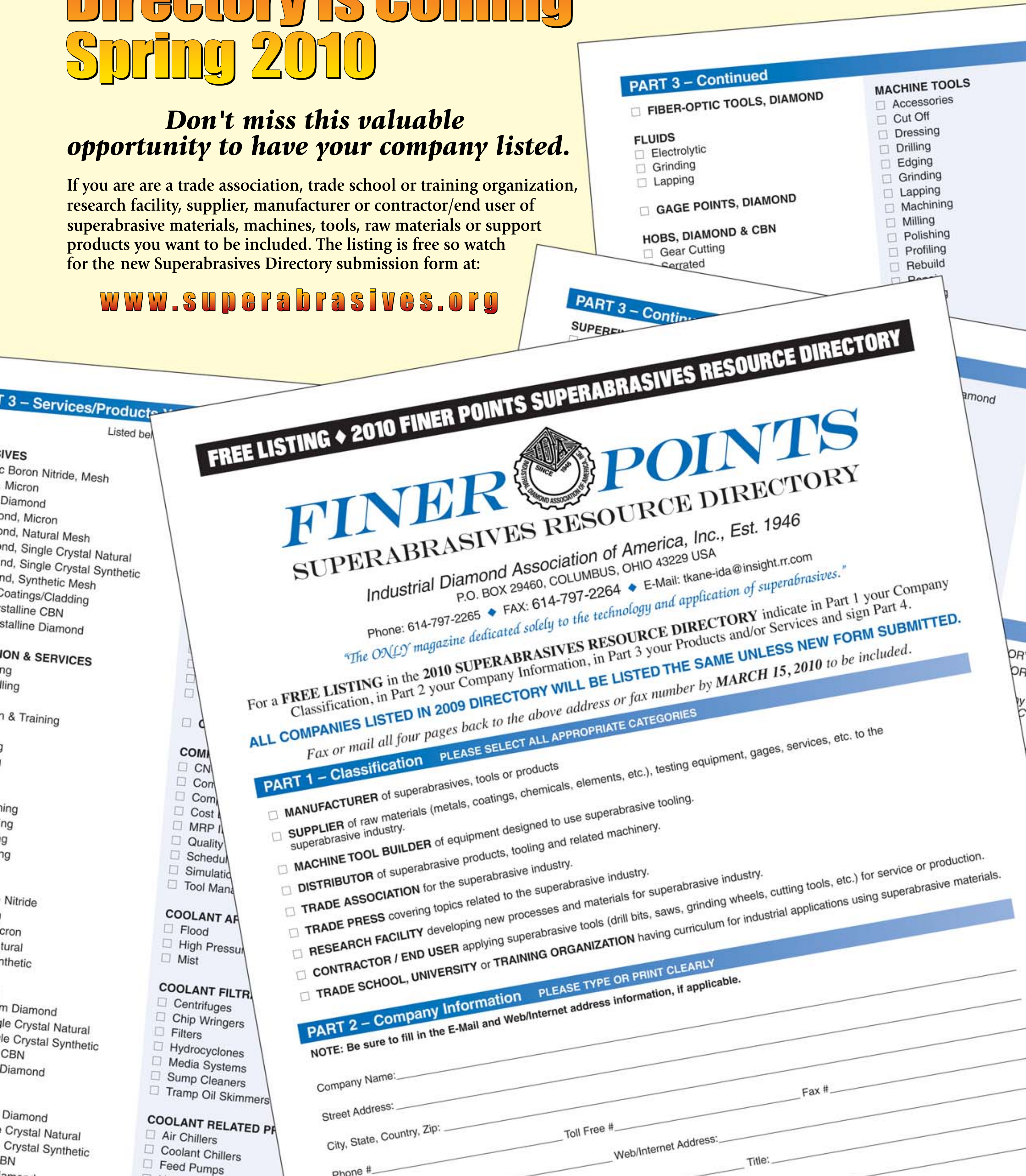

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- ☐ Serrated

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- ☐ Edging
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ond, Natural Mesh
ond, Single Crystal Natural
nd, Single Crystal Synthetic
nd, Synthetic Mesh
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stalline CBN
stalline Diamond

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Diamond
Crystal Natural
Crystal Synthetic

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- ☐ High Pressu
- ☐ Mist

COOLANT FILTR
- ☐ Centrifuges
- ☐ Chip Wringers
- ☐ Filters
- ☐ Hydrocyclones
- ☐ Media Systems
- ☐ Sump Cleaners
- ☐ Tramp Oil Skimmers

COOLANT RELATED P
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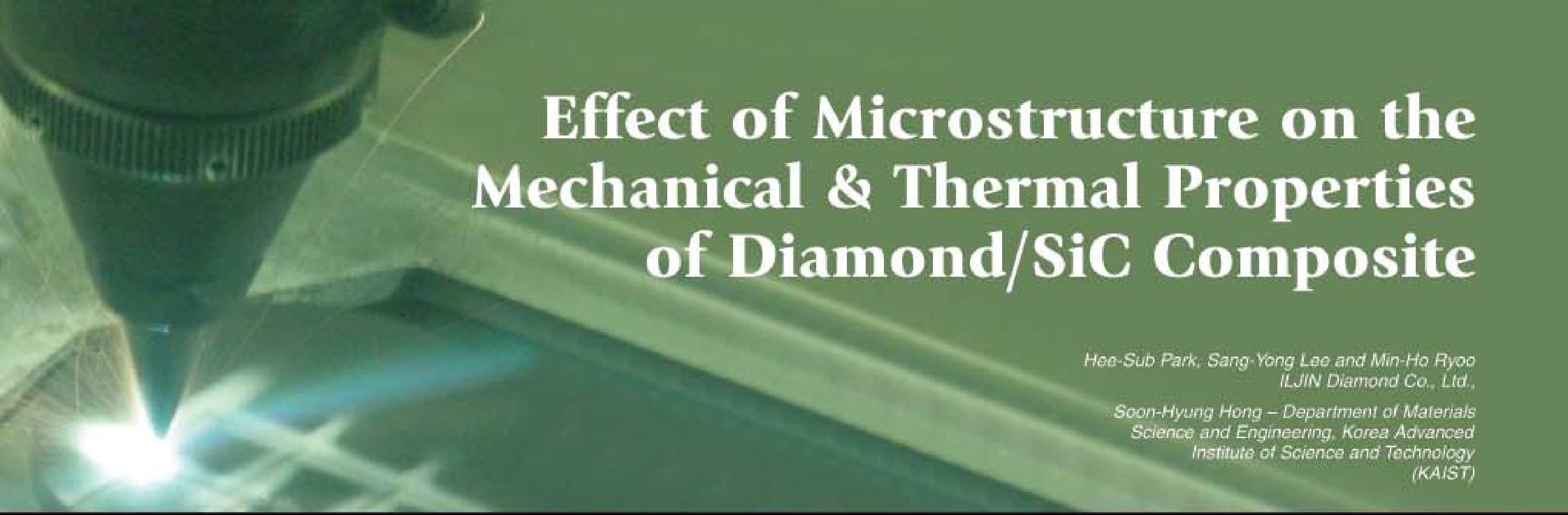
- ☐ Coolant Chillers
- ☐ Feed Pumps



Effect of Microstructure on the Mechanical & Thermal Properties of Diamond/SiC Composite

Hee-Sub Park, Sang-Yong Lee and Min-Ho Ryoo
ILJIN Diamond Co., Ltd.,

Soon-Hyung Hong – Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology (KAIST)

Diamond/SiC composites are appropriate candidate materials for heat conduction as well as high temperature abrasive materials because they do not form liquid phase at high temperature. Such a composite material consists of diamond particles embedded in a SiC binding matrix. SiC is known as a very hard material with strong covalent bonds having similar structure and thermal expansion with diamond. Interface formation plays an important role in diamond/SiC composites. Diamond/SiC composite were fabricated by HPHT sintering with different diamond content and diamond particle size, and also the effects of composition of diamond and silicon on microstructure, mechanical properties and thermal properties of diamond/SiC composite were investigated. The critical factors influencing the dynamics of reaction between diamond and silicon, such as graphitization process and phase composition, were thoroughly characterized. Key factor for good mechanical and thermal properties in diamond/SiC composites is to keep strong bonding between diamond and SiC formed from the carbon of diamond and uniformity of microstructure.

POLYCRYSTALLINE DIAMOND AND COMPOSITION CONSIDERATIONS

Diamond is the hardest material known, has high tensile & compressive strength and high wear resistance. Diamond composites with diamond-to-diamond bonds were first sintered using pressures of 6.5 GPa and temperatures of up to 2400 K for the sintering process. Liquid phase sintering techniques at several high pressure and high temperature (HPHT) have been developed to produce microcrystalline diamond composites. In most of these techniques, microcrystalline diamond powder is infiltrated at high pressure by a liquid sintering agent (cobalt, nickel, iron, and their alloys) or bonding agent like silicon. Polycrystalline diamond (PCD) materials are established materials in cutting and drill applications. While being very hard and extremely wear-resistant, poor thermal stability of the diamonds generally causes their decomposition. Cobalt is frequently used as solvent/catalyst during manufacturing, but the cobalt also leads to chemical instability of the PCD material at temperatures exceeding about 700°C. Even a trace of metal catalyst promotes graphitization of diamond crystals and thus limits practical application of PCD. As high temperatures are likely to develop in most machining processes, one of approaches to improve the poor thermal stability is to remove the metal binder phase after synthesis, e.g. by leaching the product in hot acids. The resulting material will exhibit a porous structure and therefore, whilst being relatively thermally stable, however, prone to internal oxidation. For another approach, it is possible to avoid this problem by replacing cobalt with other binders such as silicon. During the sintering process silicon reacts with diamond to form silicon carbide and this carbide acts as a bonding agent. The sintering mechanism of conventional diamond and diamond/SiC composite can be different. In case of PCD, upon heating under pressure cobalt melts and infiltrates voids between the diamond particles, which maintains hydrostatic conditions and prevents graphitization during the sintering process. Dissolution and precipitation are the main driving mechanism and the strength of PCD mainly depends on the direct bonds strength between diamonds produced by the crystallites growing together around contact area. Whereas, in diamond/SiC composite, reactive sintering plays a major role in driving densification process and reaction bonding strength between diamond and SiC is important. SiC is perfect candidate to be used as binder between diamonds because its crystallographic structure is very similar to that of diamond, and has excellent mechanical properties. SiC does not promote graphitization, has very low thermal expansion coefficient and very high melting point. In that study, novel bulk diamond/SiC composite were fabricated with diamond and silicon mixture by HPHT sintering and also the effects of composition of diamond and silicon on microstructure, mechanical properties and thermal properties of diamond/SiC composite were investigated. Main factors influencing the dynamics of reaction between diamond and silicon, such as graphitization process and phase composition, were thoroughly characterized. Silicon was used as the bonding agent because of several advantages. Melting point of silicon decreases as pressure increases, which provides a lower processing temperature that can minimize diamond graphitization. The structural similarity between the reaction product SiC and diamond builds a strong bond and the high melting point of SiC (>2200 °C) makes the obtained composites suitable for high-temperature applications. For comparison purposes, the main properties of

		Diamond	3C-SiC
Hardness	GPa	100	26
Tensile Strength	GPa	>1.2	0.25
Compressive Strength	GPa	>110	3.9
Dynamic Friction Coefficient		0.03	0.7
Density	g/cm^3	3.52	3.21
Young's Modulus	GPa	1220	410
Poisson's Ratio		0.2	0.14
Thermal Expansion Coefficient (at room temp.)	K^{-1}	1.1×10^{-6}	2.77×10^{-6}
Thermal Conductivity (at room temp.)	W/cm·K	20.0	3.6
Electric Resistivity	Ω·cm	1013-1016	102-106

Table 1: The Principal Properties of Diamond and SiC

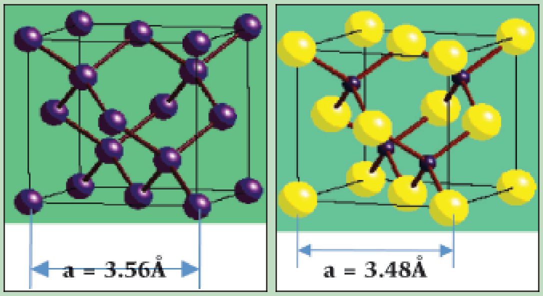


FIGURE 1: An illustration of the face centered cubic structure of a) diamond and b) 3C-SiC

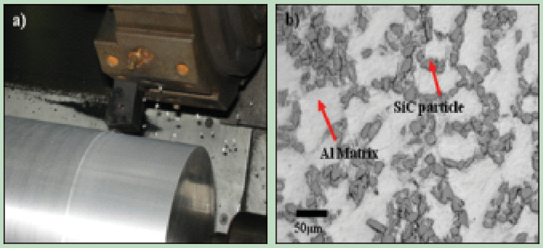


FIGURE 2: Wear tests of diamond/SiC composites in high speed turning of MMC. a) Machining of MMC, b) Microstructures of work pieces

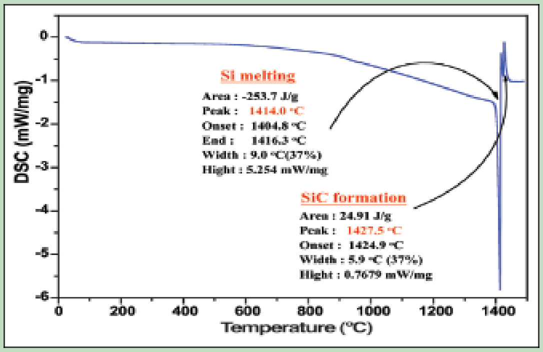


FIGURE 3: DSC curves of diamond and Si powder mixture up to 1450oC in Ar atmosphere

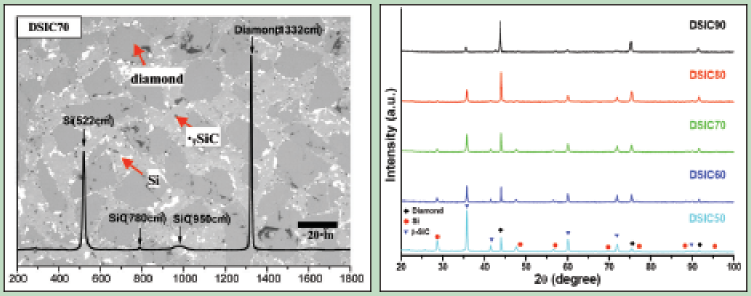


FIGURE 4: Phase analysis results by XRD and Raman spectra. a) Raman spectra of DSIC70 diamond/SiC composite, b) XRD diffraction patterns of diamond/SiC composites with 50 to 90 wt% diamond content

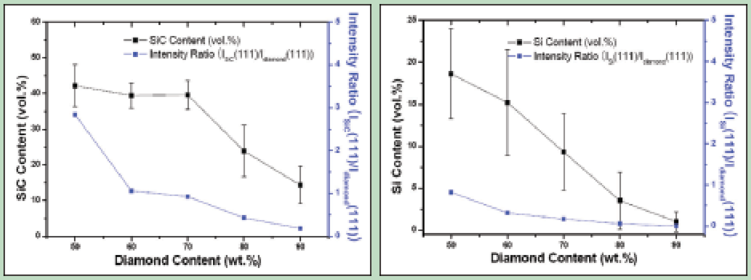


FIGURE 5: Quantitative relationship between Diamond, SiC and Si from image analysis and XRD relative intensity a) SiC content as a function of diamond content b) Remained Si content as a function of diamond content

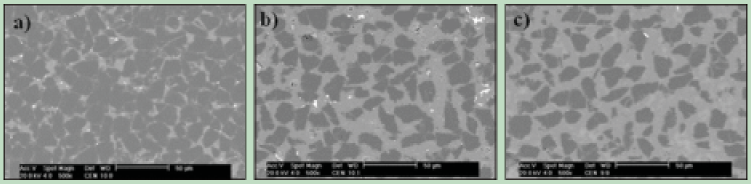


FIGURE 6: EM micrographs of diamond/SiC composite fabricated with different diamond content. a) DSIC90, b) DSIC70, c) DSIC60

silicon carbide are listed together with those of diamond in Table 1 and Fig. 1. In the last years several studies on the sintering process and mechanical properties of diamond/SiC composites have been reported. However there is little information on the relationship between the mechanical properties, the microstructure, and the corresponding fracture mechanisms in diamond/SiC composites.

EXPERIMENTAL PROCEDURES

Material and fabrication

Starting materials used in this study were synthetic diamond powder (average grain size 1.5, 5 and 29 μm grade) and Si powder (average grain size 3.5 μm). The Si powders ranging 10 to 50 wt% were mixed into diamond powders. The starting powders were mixed with ethanol for 24 h in ball mill. Mixing was carried out with care to avoid contamination from jar and ball and to obtain a uniform mixture of diamond and silicon powders. The samples were denoted as DSiC90 for 90 wt % diamond and 10 wt% Si mixtures, DSIC91 for 90wt% diamond (bi-modal particle size 29 μm +5 μm) and 10 wt% Si mixtures. The dried powders were sieved and heat-treated at 800oC in hydrogen atmosphere. A flat belt-type high-pressure apparatus to synthesize industrial diamond was used for high pressure sintering. The samples were loaded to 6 GPa at room temperature, then heated to the designed temperature at 1500oC and kept for 1 hour in diamond stable condition. The sintered compacts were ground with a diamond grinding wheel and then pieces were cut by pulse laser from large diameter discs.

Characterization

Thermal characterization of diamond and Si mixture was performed via differential scanning calorimetry (DSC) using Netzsch 404 C. A furnace rate of 10oC/min and an argon atmosphere were employed. Microstructure of diamond/SiC composites was observed by scanning electron microscopy (Philips XL30SFEG) and optical microscopy (Leica, DC-200). The phases of diamond/SiC composites were characterized by Raman spectra analysis (LabRAM HR) and an x-ray diffraction analysis (Rigaku D/Max IIIC (3kW)). Bulk density and porosity were measured by a water displacement method based on the Archimedes principle. An image-analyzing program, Matrox Inspector 2.1, analyzed composition of the composites. Preparation of the specimens for TEM observation were carried out by FIB (FEI Nova 200) containing both a focused Ga+ ion beam and a high resolution field emission scanning electron column to image the surface of this sample and identify the location of the diamond–SiC interfaces. TEM analysis by imaging and electron diffraction from different regions in the specimen was performed using FEI TecnaiTM F2 F30 TEM operated at 300 kV. Mitutoyo Hardness testing system measured the Knoop indentation hardness on the polished surface of the samples with 9.8N load. SEM analyzed the microstructure of the fractured surface, after breaking the specimens. There point bending tests and compressive strength tests were performed with a 0.5mm/min crosshead speed. Flexural strength of the composites was measured from five

	Si	Fe	Cu	Mg	Ti	Al
Workpiece: DURALCAN F3S.20S (Al-20%SiCp)	9.5-10.5	0.3 max.	0.20 max.	0.75-1.20	0.20 max.	Bal.
Machining parameter	V = 500 m/min d = 0.5 mm f = 0.25 mm/rev Coolant: Dry Insert: RNGN1204					

Table 1: Workpiece and Machining Parameter

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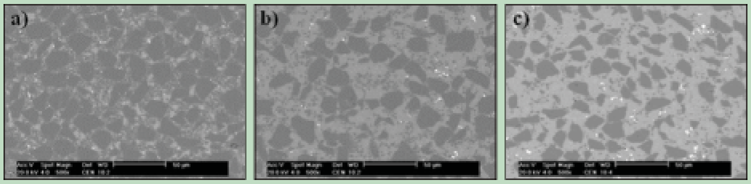

FIGURE 7: EM micrographs of diamond/SiC composite fabricated with different diamond content and bi-modal particle size. a) DSIC91, b) DSIC71, c) DSIC61

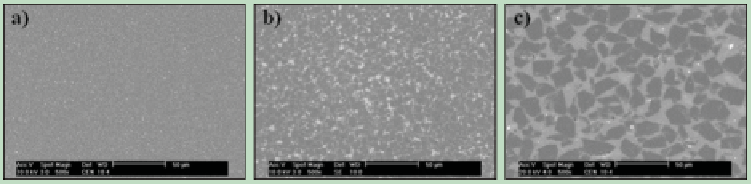

FIGURE 8: SEM micrographs of diamond/SiC composite fabricated with different diamondparticle size. a) DSIC80-1.5 µm, b) DSIC80-5 µm, c) DSIC80-29 µm

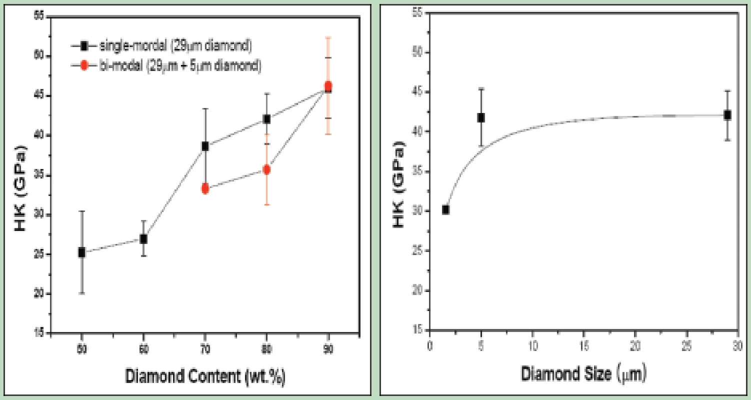

FIGURE 9: Knoop hardness of diamond/SiC composites with different a) diamond content and b) diamond particle size

specimens of diamond/SiC composites at ambient temperature using a universal testing machine, Instron5583. Compressive strength of the composites was measured from five specimens of diamond/SiC composites at ambient temperature and heat-treated five specimens of diamond/SiC composites at 800°C, 100°C and 1200°C. The fracture surfaces of the broken specimens were examined by scanning electron microscopy

Cutting Test

The wear tests are performed on a DUSAN CNC Machine. The cutting parameter and workpiece for this study is shown in Fig. 2 and Table 2. The machining investigations were carried out using Duralcan F3S.20S AlSiC metal-matrix composite. The SiC particles had an average diameter of 12-15 µm. The test material was in the form of bars of 180 mm diameter and 300 mm length. Before testing 5 mm of diameter were removed from the workpiece to avoid the influence of the harder surface layer. Duralcan is a mixture of ceramic (SiC) powder with aluminum. It is well known for its excellent mechanical and physical characteristics such as tensile

	Bulk Density (g/cm^3)	Diamond (vol%)	SiC (vol%)	Si (vol%)	Theoretical Density (g/cm^3)	Relative Density (%)
DSIC90	3.398	84.66±8.36	14.32±5.31	1.02±1.23	3.46	98.11
DSIC80	3.340	72.59±7.25	23.89±7.26	3.52±3.42	3.40	98.12
DSIC70	3.225	51.13±4.26	39.55±4.15	9.32±4.67	3.29	98.13
DSIC60	3.212	45.36±3.96	39.43±3.62	15.21±6.36	3.22	99.85
DSIC50	3.167	39.23±4.87	42.15±5.94	18.62±5.48	3.17	99.98

Table 3. A summary of quantitative analysis of diamond/SiC composite containing different amounts of diamond, SiC and Si

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Summer 2010	IMTS Preview & Machine Tools	June 30, 2010
Fall 2010	INTERTECH 2011 Preview	Aug. 31, 2010
Winter 2010/2011	Nano Diamond Materials	Nov. 30, 2010

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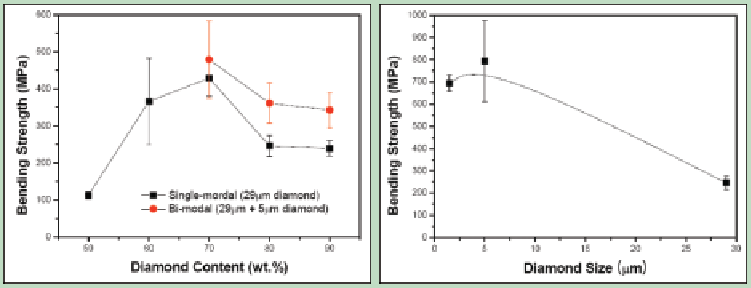

FIGURE 10: ending strength of diamond/SiC composites with different a) diamond content and b) diamond particle size

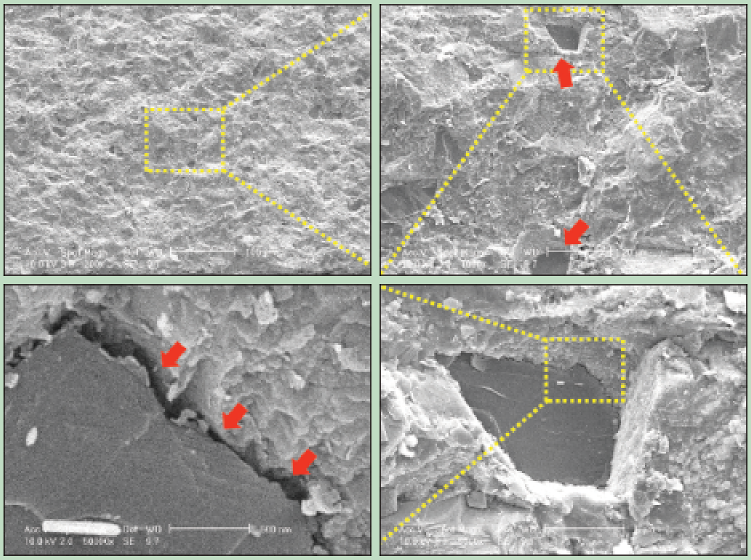

FIGURE 11: SEM micrographs of the typical fracture surface of diamond/SiC composite

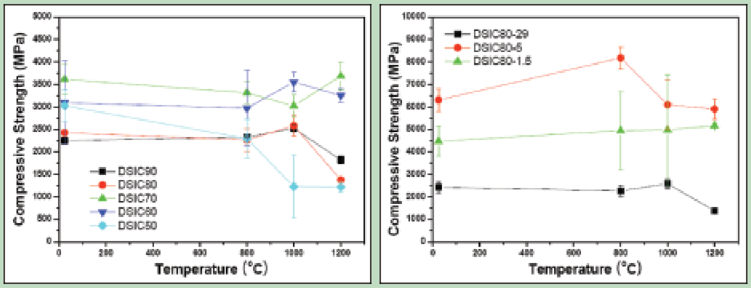

FIGURE 12: Compressive strength of diamond/SiC composites with different a) diamond content and b) diamond particle size after heat-treated at 800oC, 100oC and 1200oC in air

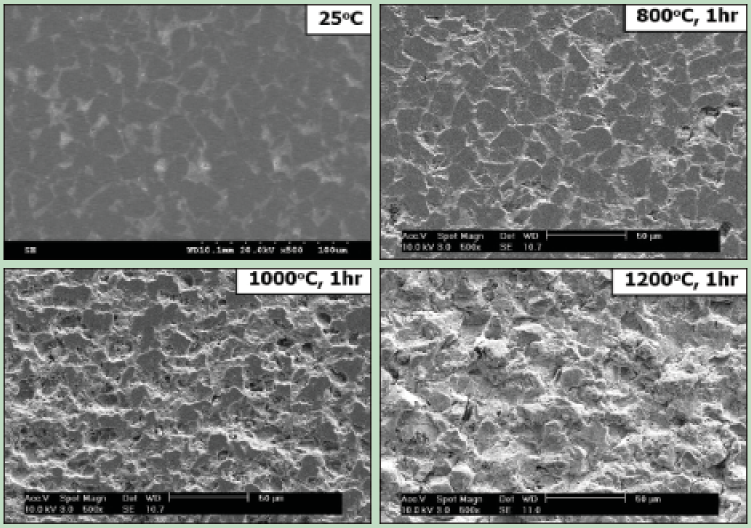

FIGURE 13: SEM images of typical microstructure of the oxidized composites after heat treatment in air atmosphere.

properties, hardness, elastic modulus and exceptional corrosion resistance in natural and salt atmosphere. Due to its excellent wear behavior, damping factor and lightness Duralcan is in many applications a perfect replacement for pieces actually cast in steel and grey iron. Typical applications range from bicycle frames, automotive tire studs to train brake discs and automotive drive shafts, brake drums and discs, back plates for friction materials and gear box components.

RESULTS AND DISCUSSION

Microstructure Characterization

Differential scanning calorimetry (DSC) In order to study the reaction behavior between diamond and silicon powder used in this work, diamond and silicon mixtures were heated in a thermal analyzer. Fig. 3. shows DSC curves of diamond and Si powder mixture up to 1450oC in Ar atmosphere. Si metal melting point is 1414oC. About 1430oC, chemical reaction between carbon from diamond and liquid Si forms a new SiC. As the pressure and temperature increase, Si is melted at lower melting point and SiC phases are nucleated on diamond crystal, near the surface defect. The reaction during sintering can be expressed as follows: $C_{diamond}(s) + Si(l) \rightarrow \beta\text{-SiC}$.

Phase Analysis by XRD and Raman Spectra

Fig. 4. a) Is the result of Raman spectra of diamond/SiC composite. Peaks due to diamond, β-SiC phases and silicon phases are observed. But the graphite doublet peak is not observed such as disordered D band 1310cm-1, graphic G band 1590 cm-1. XRD Pattern of diamond/SiC composite is shown in Fig. 4. b). The existence of diamond, β-SiC phases and silicon phases were found in all patterns but trace of graphite and β-SiC was not found. This indicates that the formation of β-SiC has taken place and that residual Si still exists. As the diamond content increased, peak intensity of SiC and Si relatively decreased and relative intensity of diamond increased.

Density

Density results and quantitative analysis of Diamond, SiC and Si from image analysis are summarized in Table 3. The theoretical density is calculated by assuming that the whole of silicon in the starting material completely reacts to diamond. Fig. 5. shows quantitative analysis of Diamond, SiC and Si from image analysis and XRD relative intensity. As the diamond content increased, relative intensity of SiC and Si decreased. This is similar to image analysis of microstructure. Relative densities of the samples were increased with decrease of diamond content. Diamond/SiC composite by HPHT in pressure apparatus synthesizing diamond showed almost full density.

Fig. 6. ~ Fig. 8. Show SEM micrographs of diamond/SiC composite with different diamond content and diamond particles size. This microstructure shows uniform distribution of diamond particles in SiC matrix. Dark grey particles are diamond, grey matrix phase are SiC and the white phase is unreacted Si without graphite or any other additional phases. Various diamond/SiC composites were prepared to investigate diamond content, diamond particle size and bi-modal effect.

Knoop Hardness

The results of Knoop indentation hardness of the polished surface of the diamond/SiC composites are illustrated in Fig. 9. The range of the hardness was between 26 and 46 GPa. As the diamond content and diamond size increased, Knoop hardness of diamond/SiC composite increased. The hardness of bi-modal composite was lower than that of singlemodal composite. Ideal hardness of diamond and SiC were reported to be 70 GPa and 25 GPa, respectively. From these data and simple rule of mixtures, the ideal hardness of DSIC90 was estimated to be about 55 GPa. The maximum hardness of DSIC90 is about 84% of the estimated value. The degradation of hardness of DSIC90 sample may be attributed to the relatively weak intergranular bonding strength.

Bending Strength

Fig. 10. shows bending strength as a function of diamond content and diamond size for diamond/SiC composite. 70wt% diamond/SiC composite exhibited a higher bending strength. And at same diamond content, bimodal composite had a higher bending strength about 35% The higher bending strength values 70wt% diamond/SiC composite is most likely because of lesser amount of Si and porosity in it. Also, at 80wt% diamond content, diamond/SiC composite fabricated by 5 _m diamond particles showed the highest bending strength about 800 MPa. As shown on Fig. 11. of fractography of diamond/SiC composite, fracture surfaces of C/SiC composite revealed that a cleavage type fracture indicating brittle fracture behavior. Fracture surfaces indicate that the crack propagated without any interaction with the microstructure. Diamond pullout and cracking is observed in interface between diamond and SiC. This indicates that the critical factor in ensuring good mechanical properties in diamond/SiC composites is to keep strong bonding between diamond and SiC.

Compressive Strength

Fig. 12. shows bending strength as a function of temperature for diamond/SiC composite made from different diamond content and diamond size. There was relatively little compressive strength loss at temperatures up to 1000oC in above 60wt% diamond composites. The degradation of compressive strength above 1000oC was due to the softening of the residual silicon and the development of cracks caused by the oxidation of diamond and remained silicon at high temp. DSIC80-5 compact showed a good compressive strength and thermal stability in agreement with hardness and bending strength result. Fig. 13. shows SEM image of microstructure of the oxidized composites after heat treatment in air atmosphere. The degradation of microstructure of diamond/SiC composite was increased with increase of oxidation temperature. The void in the surface from oxidation of diamond and silicon act as stress concentrators for crack initiation and growth during compressive strength test.

Fig. 13. a) shows wear behavior of diamond/SiC composite after machining the same amount of workpiece Duralcan. As the diamond content in composite increased, flank wear resistance increased. At the same diamond content, bi-modal composite had higher wear resistance. Fig. 13. b) is wear behavior of diamond/SiC composite with different diamond particle size after machining the same amount of workpiece. Fine size diamond/SiC composite showed sharp edge shape and uniform wear properties after machining. DSIC80-5 had optimum wear properties because of diamond-SiC bonding strength in agreement with previous mechanical properties results. SEM images of typical tool wear of diamond/SiC composite with different diamond size are shown in Fig. 14. At coarse diamond/SiC composite, small breakouts were detected in large magnifications. Strong adhesive effects can be observed when turning the aluminum MMC. The abrasive particles of the MMC material cause a significant flank- and crater wear on diamond layer.

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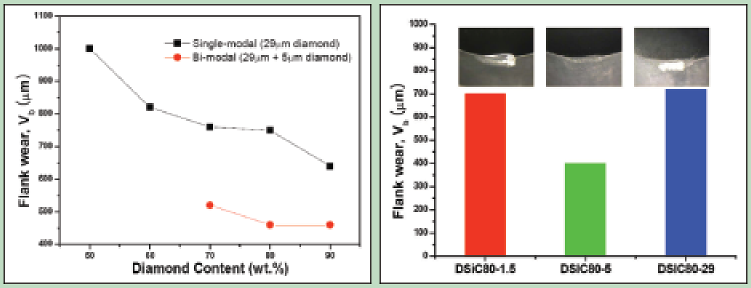

FIGURE 13: Wear behavior of diamond/SiC composites with different a) diamond content and b) diamond particle size.

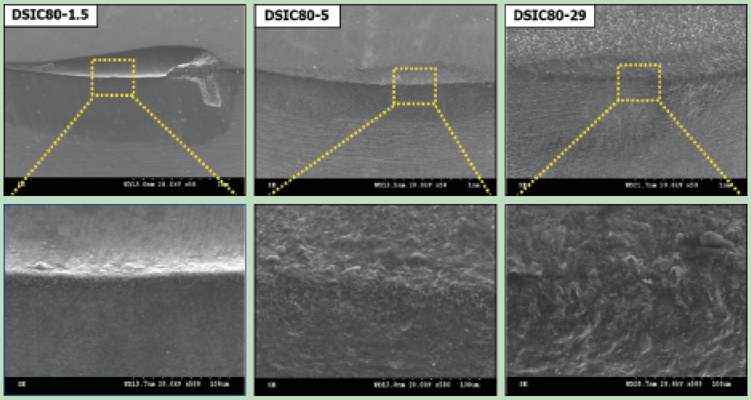

FIGURE 13: SEM images of typical tool wear of diamond/SiC composite with different diamond size.

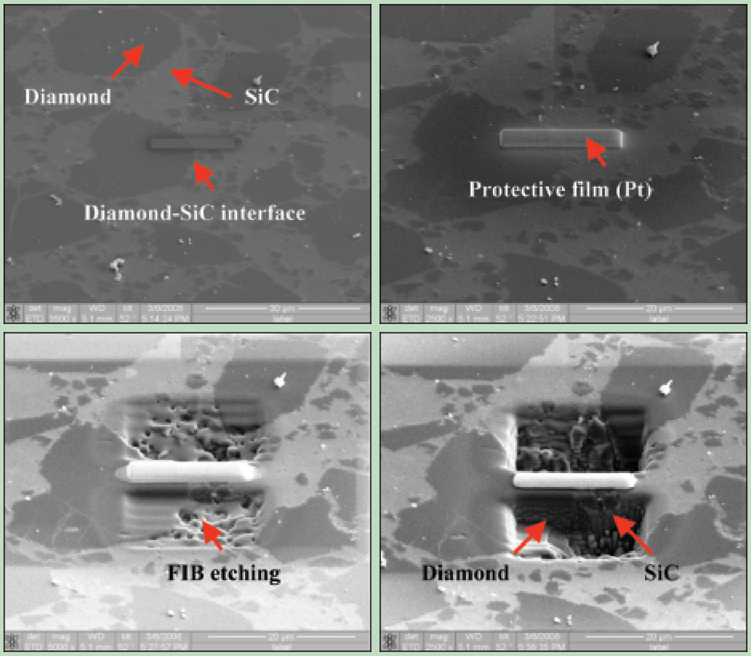

FIGURE 14: EM sample preparation process using FIB etching.

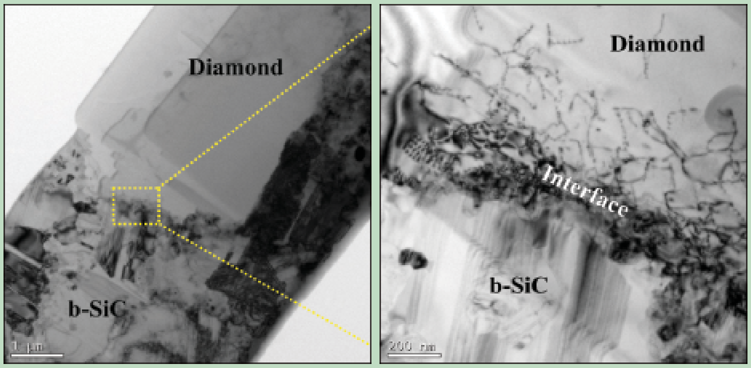

FIGURE 15: TEM image of diamond-SiC interface in diamond/SiC composite fabricated by HPHT process.

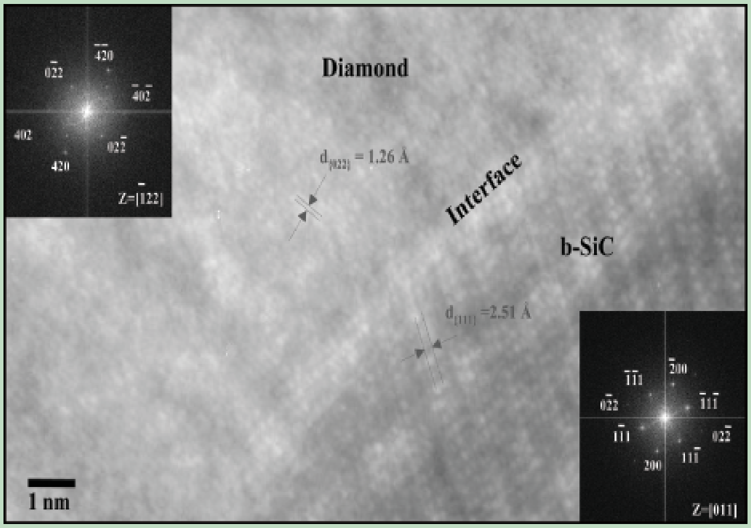

Figure 16: HRTEM image of diamond-SiC interface in diamond/SiC composite fabricated by HPHT process.

TEM Observation

TEM sample preparation for analysis of diamond-SiC interface was carried out by FIB milling. FIB technique was used for site-specific micromachining of TEM lamella. Diamond-SiC interface for analysis was decided and coated by pt for protection from ion beam and FIB etching continue to proceed. After FIM etching and polishing, TEM sample of 100nm thickness was obtained. Fig. 15. is TEM image of diamond-SiC interface. There were high defect density near the diamond-SiC interface such as dislocation, stacking fault and micro twin. Diamond-SiC Interface consisted of high defect density might exhibit high thermal resistance and grain boundary fracture. SiC grains deformed more severely than diamond grain due to high pressure and high temperature sintering. Fig. 16. is HRTEM Image of diamond-SiC interface. It is difficult to perform high resolution imaging on interface because of a very high defect density at interface and ion beam damage during specimen preparation. Complex interface structure accommodates the misfit between diamond and SiC. ■

CONCLUSIONS

Diamond/SiC composites were fabricated by HPHT in pressure apparatus synthesizing diamond with different diamond content and diamond particle size. Diamond/SiC composites showed almost full density and graphite phase was not observed from diamond/SiC composite by XRD and Raman spectra. As the diamond content increased, the content of SiC phase and Si phase decreased. TEM observation reveled high defect density near the diamond-SiC interface. Mechanical and thermal properties of diamond/SiC composite strongly depended on diamond content and diamond particle size. As the diamond content and diamond size increased, Knoop hardness of diamond/SiC composite increased. Bending strength of DSIC80-5 diamond/SiC composite showed the highest bending strength (800MPa) because of lesser amount of Si and porosity in it. Diamond/SiC composite of bimodal particles showed higher bending strength than single-modal composite. There was relatively little compressive strength loss at temperatures up to 1000°C. Wear test results were in good agreement with bending strength and compressive strength. The critical factor in ensuring good mechanical and thermal properties in diamond/SiC composites is to keep strong bonding between diamond and SiC formed from the carbon of diamond and uniformity of microstructure.

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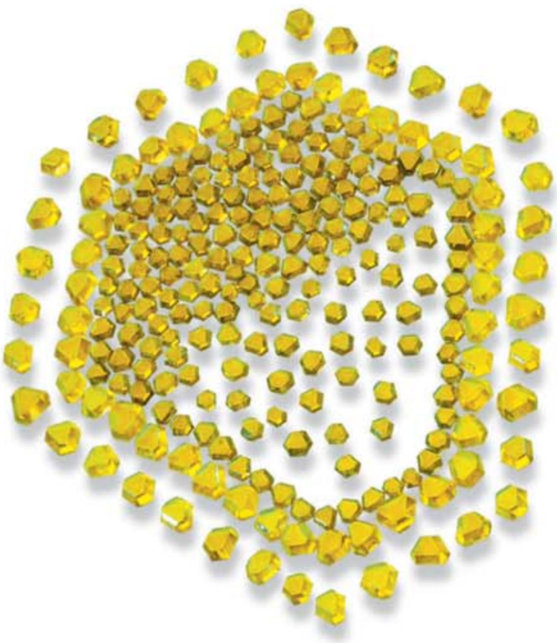

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